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DOCTOR OF PHILOSOPHY

Pelvic Positioning and Acetabular Orientation in Total Hip Replacement

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Award date:
2019

Awarding institution:
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Pelvic Positioning and Acetabular Orientation in Total Hip Replacement

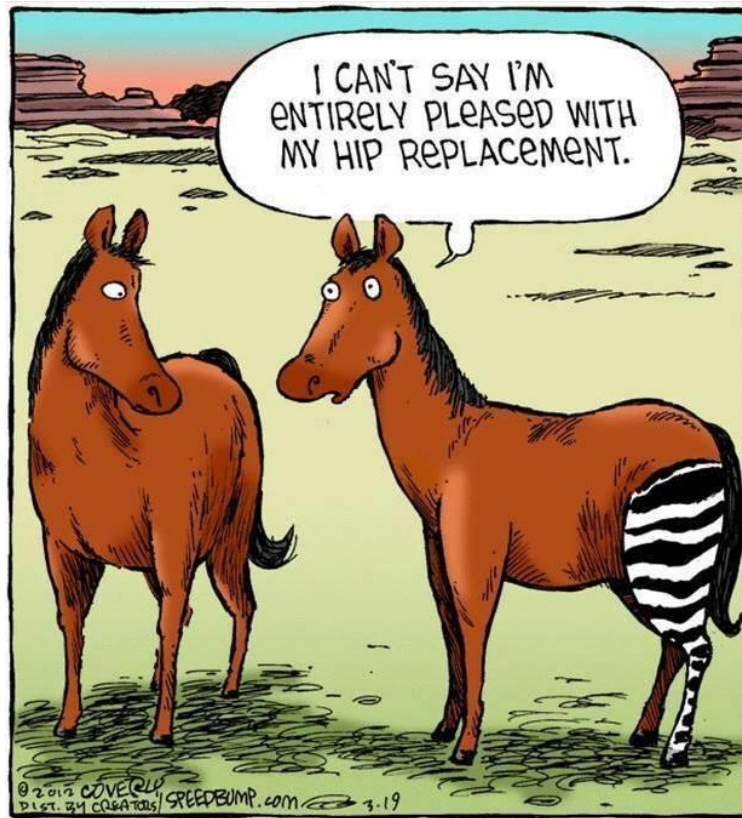
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A thesis submitted to Queen's University Belfast

for the Degree of Doctor of Philosophy

School of Mechanical and Aerospace Engineering

May 2019



*“Anyone who has never made a mistake has never
tried anything new” - Einstein*

Summary

Mal-orientation of the acetabular component can induce negative outcomes such as dislocation and subsequently a loss of patient satisfaction. Currently, a wide range of acetabular component orientations are observed on post-operative radiographs, despite the use of fixed intra-operative target angles. This work sought to answer the question of how pelvic orientation affects acetabular cup orientation in current practice and whether it can be accounted for without the use of expensive tools or additional radiation exposure.

To assess the influence of post-operative pelvic positioning relative to the radiographic film, a new computational tool was developed that allowed three-dimensional reconstruction of the pelvis and acetabular component from a single two-dimensional radiograph. Use of this tool enabled true measures of acetabular orientation to be determined (relative to the pelvis as compared to the radiographic reference frame which is subject to magnification errors). True measures of acetabular orientation exhibited reduced variability when compared to conventional 2D measures of radiographic acetabular orientation; inclination variability was reduced by 22% when applied to a clinical cohort.

Pelvic external / internal rotation (about the longitudinal axis) was found to be the primary mode of intra-operative pelvic mal-rotation that contributed to differences between operative and true post-operative measures of acetabular orientation. In practice this may be reduced by using a new coronal alignment guide developed as part of this research (mean error, $0.60^{\circ} \pm 0.68^{\circ}$). To account for intra-operative pelvic mal-rotation, when using the TAL approach, in the absence of any other intervention, orthopaedic surgeons should aim for an operative inclination that is 9° less than their true post-operative target.

The tools developed within this research have the potential to be adapted into surgical practice for total hip replacement. If implemented, they could help reduce inclination variability, increase survivorship, and improve patient satisfaction.

Acknowledgements

A special thanks to my supervisory team Dr Alex Lennon, Professor Nicholas Dunne, Professor David Beverland and Dr Janet Hill for your continued support and advice throughout. To John O'Connor, who has also been known to associate with this circle, thanks for being a solid wall. I can't count the number of ideas that have been bounced off you.

For the many moments of madness that ensued throughout my time on the third floor PhD office, cheers! Thank you for being lighthearted. A projectile free work environment will be hard to adapt to.

To Janine Blainey and Aiden Rooney, a thankful note for your perseverance and your continued help with the Transverse Pelvic Line Study. Thank you for assisting where an engineer could not and for your help with recruitment. Many special thanks to all those who volunteered.

To the Windsor ladies who have put up with me as a house mate for many a year, the thing is, I've finished writing my thesis and will resume contact presently. Thank you for the laughs, of which there were many, the mid-night jaunts to cave hill (which can be surprisingly hard to find in the dark), our second home at McDonalds and our scenic trips to Lurgan. Stay quackers!

Thank you to all of those you have inspired me to get to where I am today. To Mrs Aikken and Mr White, great teachers who helped build the foundations of my education. Last but not least, a great thank you to my loving parents, whom pushed me from day one. To my Dad who has shown me what hard work can achieve and to my Mother for whom there is a solution to every problem. To my siblings, I like you strongly.

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ONE

Introduction

1.1 Total Hip Replacement

Within the United Kingdom (UK), 92% of primary total hip replacements (THR) occur following a diagnoses of osteoarthritis (OA).¹ Severe OA results in bone-on-bone articulation following a loss of cartilage from the hip joint surfaces. This distorts the natural geometry of the hip joint, which causes reduced mobility and increased pain. To combat these symptoms, an orthopaedic surgeon can implant an acetabular and femoral component to restore the native joint geometry and mobility (Figure 1.1).

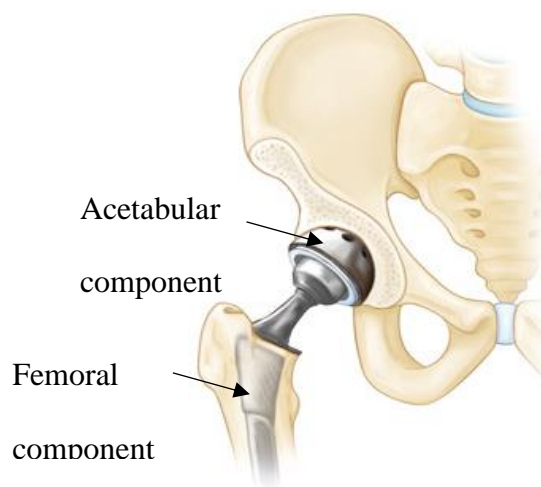


Figure 1.1 Hip implant components²

1.2 Pelvic Anatomy

The pelvis consists of two hip bones. Each hip bone began as three separate parts: (1) the ilium, (2) the ischium, and (3) the pubis (Figure 1.2). These are fused together during growth. In the region where the three bones meet, a socket is formed known as the acetabulum (Figure 1.3). The hip bones join anteriorly (towards the front) at the pubic symphysis and posteriorly (towards the back) at the sacrum. The anterior pelvic plane (APP) is a triangular plane that is formed by the two anterior superior iliac spines (ASIS) and the pubic symphysis (Figure 1.4). The transverse acetabular ligament (TAL) is a ligament that crosses the notch of the acetabulum (Figure 1.3).

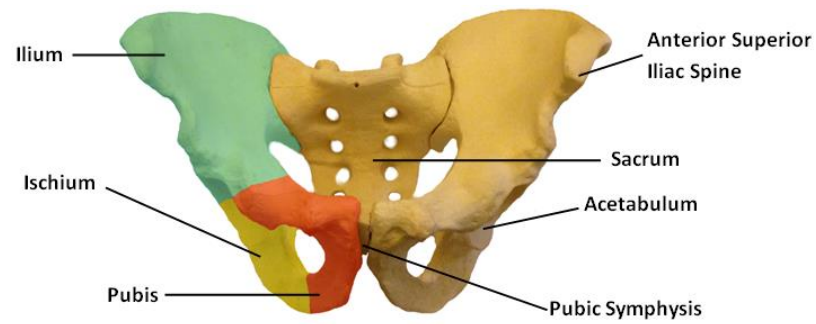


Figure 1.2 Pelvic anatomy

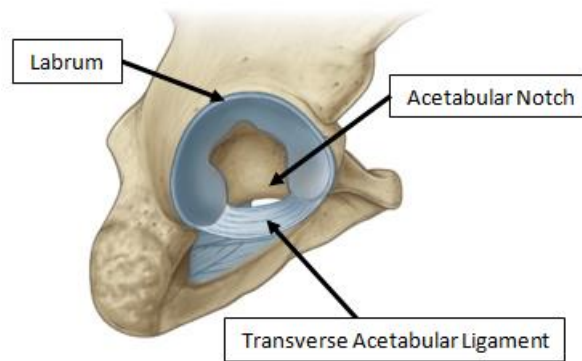


Figure 1.3 The acetabulum and transverse acetabular ligament³

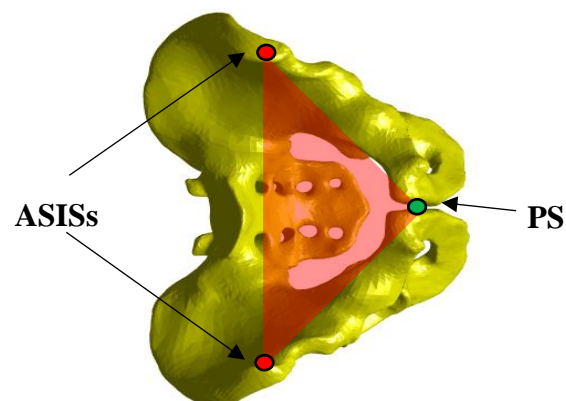


Figure 1.4 The anterior pelvic plane is formed by the anterior iliac spines (ASIS) and the pubic symphysis (PS)

1.3 Femur Anatomy

The femur or thigh bone (Figure 1.5) is the longest and strongest bone in the body.⁴ Its key anatomical features include the femoral head, femoral neck, greater and lesser trochanters, femoral shaft, and the medullary canal (Figure 1.6).

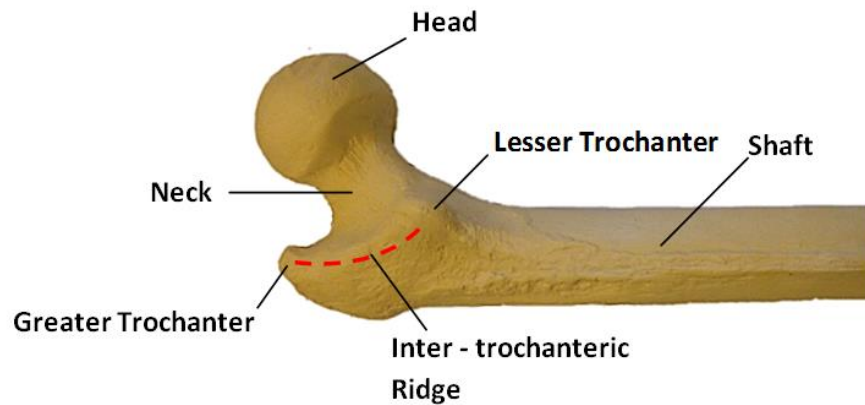


Figure 1.5 Femur anatomy

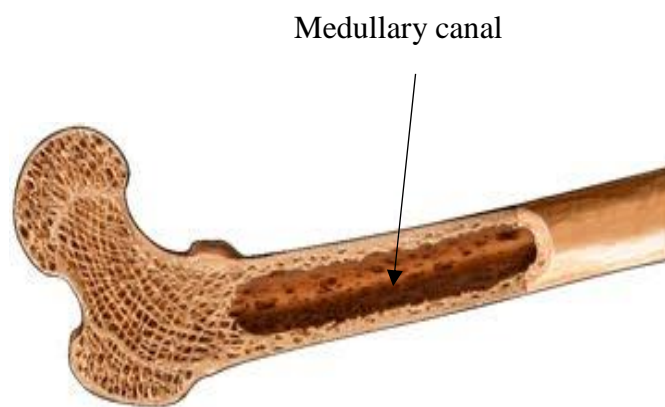


Figure 1.6 Medullary canal⁵

1.4 Body Anatomical Planes, Axes, and Hip Joint Motions

The body has three mutually perpendicular anatomical planes: the (1) sagittal, (2) coronal, and (3) transverse planes. The anterior–posterior (AP), longitudinal and medio-lateral axes reside on each of these three anatomical planes respectively (Figure 1.7).

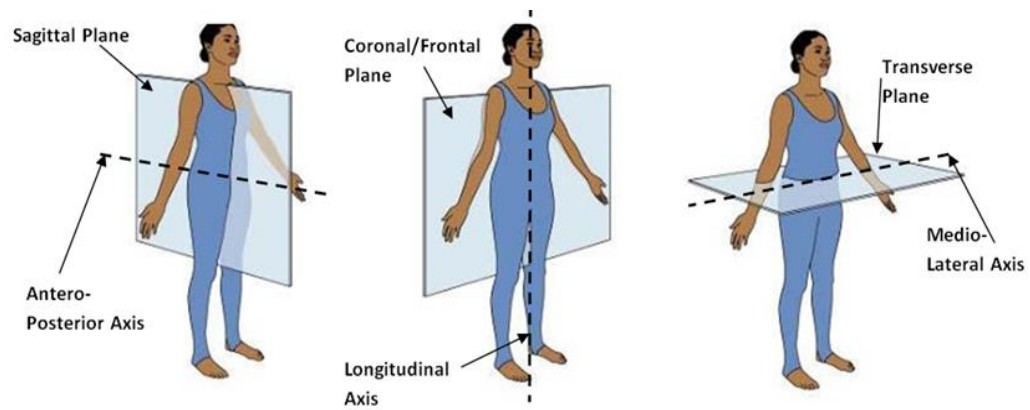


Figure 1.7 Anatomical planes and axes⁶

The hip joint is a ball and socket joint. In a natural hip (no THR), it is formed by the articulation between the bony femoral head (ball) and the acetabulum (socket). The hip joint has three degrees of freedom: flexion/extension, abduction/adduction and internal/external rotation (Figure 1.8).⁷

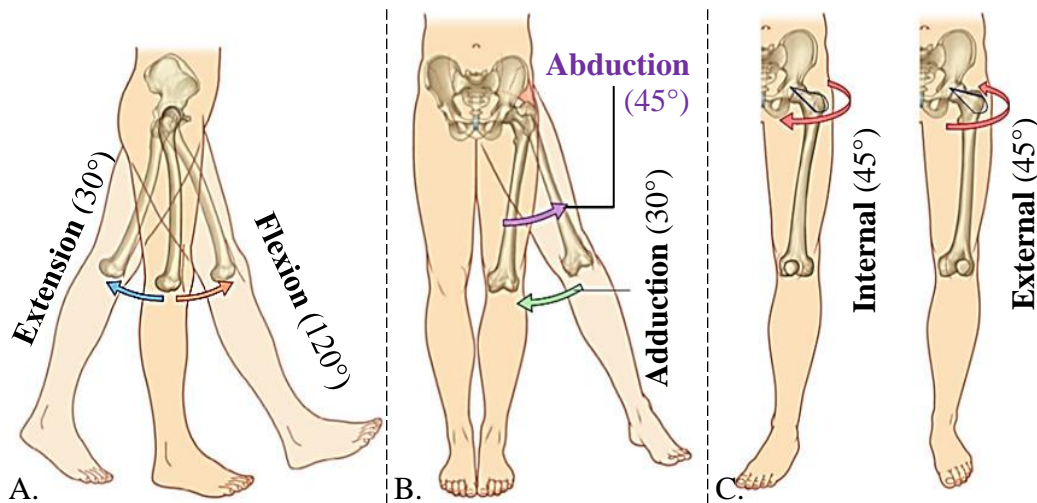


Figure 1.8 Maximum values for normal hip joint range of motion according to the American Academy of Orthopaedic Surgeons: a) flexion and extension in the sagittal plane, b) adduction / abduction in the coronal plane and c) internal / external rotation in the transverse plane.^{7,8}

1.5 THR Surgical Procedure

During THR, a prosthetic acetabular component is inserted into the bony acetabulum and a prosthetic femoral component is inserted into the medullary canal of the femur. Following a surgical incision to allow access to the affected hip joint, the surgeon will dislocate the hip joint by removing the bony femoral head from the acetabulum. To allow for insertion of the femoral component, the bony femoral neck is resected and the native bony femoral head removed (Figure 1.9a). In preparation for insertion of the acetabular component, dead tissue and unwanted bone is removed from the acetabulum by reaming (Figure 1.9b). As with the acetabulum, prior to insertion of the femoral stem component, the medullary canal is reamed (Figure 1.9d).

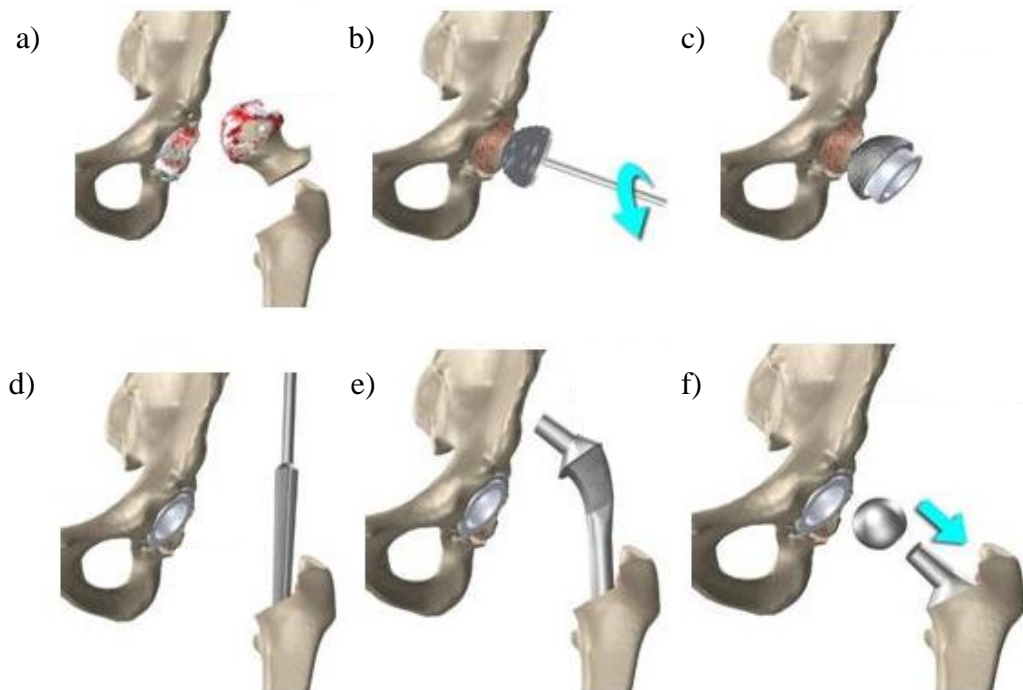


Figure 1.9 Total replacement procedure:⁹ a) resection of the femoral neck, b) reaming of the acetabulum, c) insertion of the acetabular component, d) reaming of the medullary canal, e) insertion of the femoral stem component, f) attachment of the femoral head component.

1.6 Patient Positioning

There are two main patient positions when undergoing a THR procedure: (1) supine and (2) *lateral decubitus* (LD). In the supine position, the patient is lying on their back, whilst in the LD position, the patient is lying on their side (Figure 1.10). Within the UK, LD positioning is used in 90% of THR procedures.¹⁰ During THR, the patient is maintained in the LD position by using supports. These supports typically engage the ASISs and/or the pubic symphysis anteriorly. When in the LD position, theoretical neutral intra-operative pelvic orientation is achieved when the pelvic sagittal plane is parallel to the theatre floor and the anterior pelvic plane is parallel to the long axis of the theatre table (Figure 1.11).

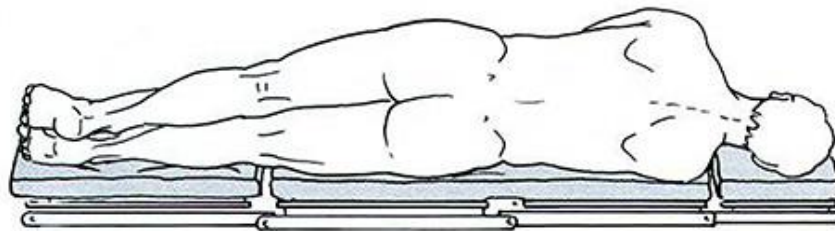


Figure 1.10 Lateral decubitus patient positioning.¹¹

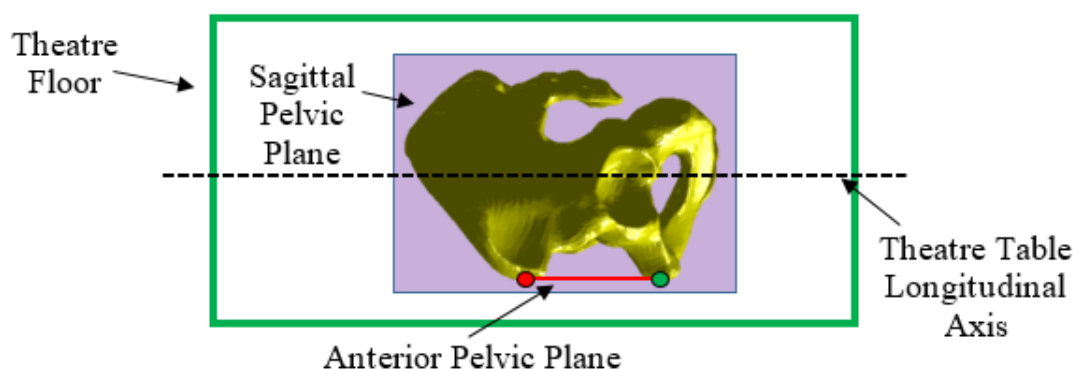


Figure 1.11 Neutral intra-operative positioning of the pelvis in LD positioning.

1.7 Acetabular Orientation

Acetabular component orientation impacts the successful outcome of a THR.¹²⁻¹⁵ During THR, the acetabular component is inserted into the acetabulum using an introducer. The acetabular axis is an axis that is perpendicular to the face of the acetabular component being inserted and collinear with the handle of the introducer (Figure 1.12). Acetabular orientation is defined by two angles: (1) inclination and (2) version. Measures of inclination and version have been previously defined with respect to the anatomical, operative and post-operative radiographic references frames:¹⁶

- Anatomical inclination is the angle between the body longitudinal axis and the acetabular axis.
- Anatomical version is the angle between the medio-lateral axis and the acetabular axis when this is projected onto the transverse plane.
- Operative inclination (OI) is the angle between the acetabular axis and the sagittal plane (Figure 1.12a).
- Operative version (OV) is represented as the angle between the acetabular axis and the longitudinal axis of the body when projected onto the sagittal plane (Figure 1.12b).
- Radiographic inclination (RI) angle is the angle that is formed between the acetabular axis and the body longitudinal axis when projected onto the coronal plane.
- Radiographic version (RV) is represented as the angle between the acetabular axis and the coronal plane.

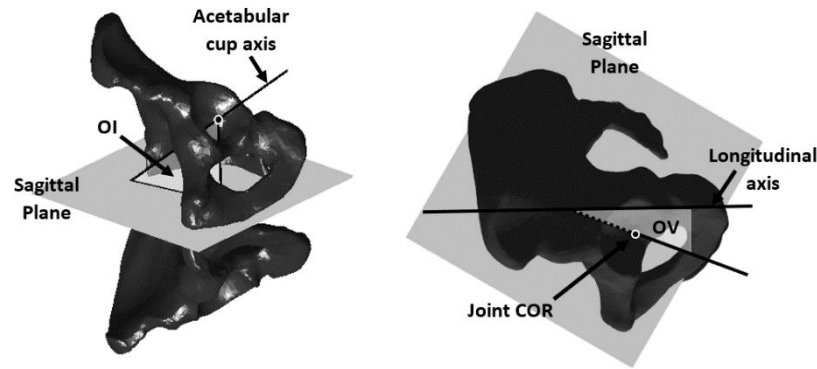


Figure 1.12 Operative inclination (OI) and version (OV).

In practice measures of RI can be obtained by determining the angle between the long axis of the projected cup face and the inter-tear drop line (Figure 1.13). Estimates of RV can be obtained from the relative diameters of the projected cup face (Figure 1.13).

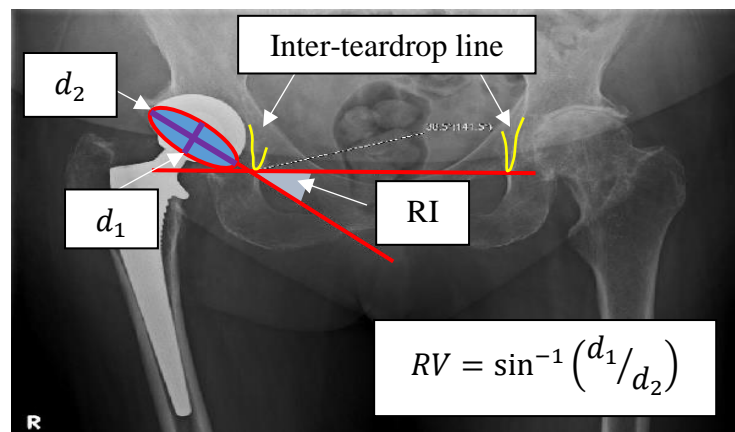


Figure 1.13 Measures of radiographic inclination (RI) and version (RV) taken in practice.

1.8 Hip Centre of Rotation

The hip centre of rotation (HJC) is the centre of the acetabulum with respect to the pelvis. Femoral head centre (FHC) is the centre of the femoral head with respect to the femur. When these two coincide, the hip is regarded as concentrically reduced. Therefore, in the latter situation, HJC can be approximated by fitting a circle to the native or prosthetic femoral head on an anterior-posterior radiograph of the pelvis

(Figure 1.14).¹⁷⁻¹⁹ The relative location of the hip HJC and FHC can be described using two terms: (1) height and (2) offset.

1.8.1 Height

Hip joint centre height is defined as the perpendicular distance between a fixed point on the pelvis, which is usually the inter-teardrop line (Figure 1.14, line AA), and the hip HJC¹⁸ (i.e. with respect to the pelvis). Femoral head centre height is defined as the perpendicular distance from FHC to a fixed line on the femur drawn perpendicular to the femoral axis, usually at the level of the midpoint of the lesser trochanter (i.e. with respect to the femur). Thus, the measurements of acetabular HJC height and femoral FHC height can be made independently of each other. In contrast, global height is the distance from a fixed point on the pelvis to a fixed point on the femur, which (with the above definition) would be the inter-teardrop line and the lesser trochanter.

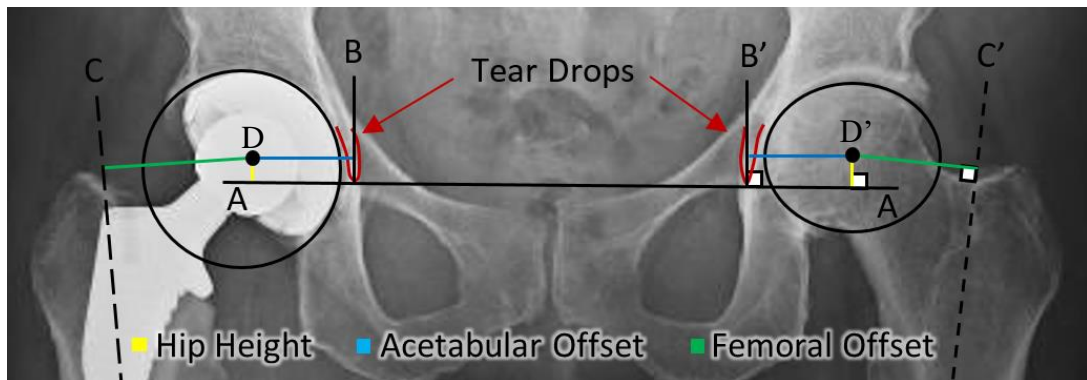


Figure 1.14 Hip joint centre measurements for the native and reconstructed hip: A-A Inter-teardrop line, B-D Acetabular Offset, C-D Femoral Offset, AA-D Hip Height.

1.8.2 Offset

Acetabular offset (AO) is defined as the horizontal distance from a line drawn perpendicularly through the inter-teardrop line at the centre of the teardrop and the HJC.²⁰ Femoral offset (FO) is defined as the perpendicular distance between FHC and

the femoral anatomical axis.²¹ Thus, again, the measurements of acetabular HJC offset and FHC offset can be made independently of each other. In contrast, global offset (GO) is the distance from a fixed point on the pelvis to a fixed point on the femur, which (with the above definition) would be the horizontal distance from the teardrop to the femoral anatomical axis.²²⁻²³

1.9 Navigation

Surgical approaches for orientating the acetabular component intra-operatively can be categorised by two main classifications: (1) external and (2) internal landmark-based. External landmark-based approaches aim for landmarks that are external to the patient intra-operatively. External landmarks typically include the theatre floor, theatre wall, and the longitudinal axis of the theatre table. Both the freehand and the mechanical alignment guide (MAG) approaches rely on the use of external landmarks. Freehand positioning achieves operative inclination and version relative to the theatre floor and table longitudinal axis as judged by eye (Figure 1.15a). The MAG approach uses the same external landmarks as the freehand approach. However, the orthopaedic surgeon also has the assistance of an angled bracket attached to the introducer when orientating the acetabular component intra-operatively (Figure 1.15b).

Internal landmark-based approaches orientate the acetabular component intra-operatively relative to internal landmarks such as the anterior pelvic plane. Computer aided orthopaedic surgery (CAOS) is an internal landmark-based approach. With CAOS, a computer is used to register intra-operative anatomic landmarks to a virtual model of the hip joint.²⁵ Image-based CAOS builds a patient-specific virtual model from pre-operative computed tomography (CT) scans of the patient.²⁵ Image-free CAOS morphs a kinematic model to the registered intra-operative landmarks.²⁵

Following registration, a tracker attached to the patient enables an orthopaedic surgeon to track the orientation of the hip implant components relative to the bony anatomy.²⁵

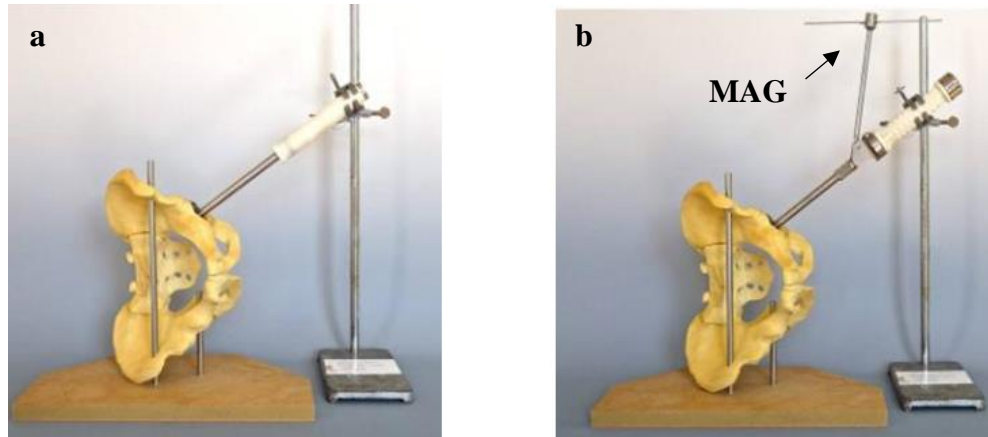


Figure 1.15 a) Freehand b) Mechanical alignment guide (MAG).²⁴

A hybrid approach that uses both internal and external landmarks is the TAL approach. For this approach, operative version is controlled by placing the acetabular face parallel to and just deep of the TAL (Figure 1.16).²⁶ This restores the native version of the joint but not its inclination as the TAL approach still relies on the use of the external theatre floor for controlling operative inclination.

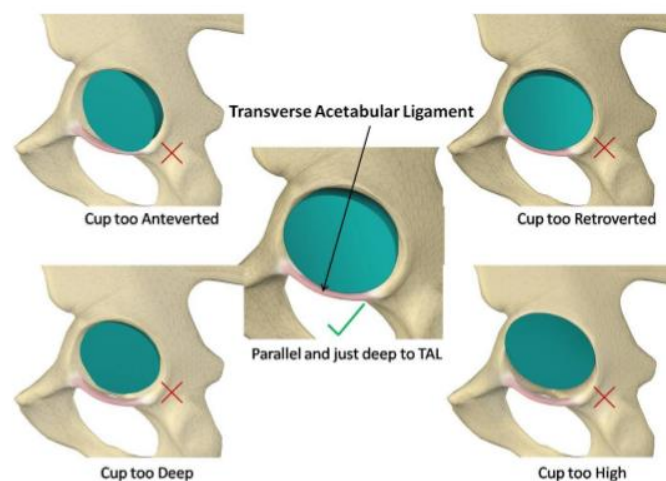


Figure 1.16 Transverse acetabular ligament approach.²⁶

1.10 Pelvic Orientation

The pelvis has three axes of rotation: (1) rotation about the longitudinal axis of the pelvis is regarded as external/internal rotation; (2) rotation about the pelvic anterior-posterior axis is adduction/abduction and (3) posterior/anterior tilt is rotation of the pelvis about its medio-lateral axis (Figure 1.17). During THR surgery, the pelvic orientation may have deviated from its theoretical neutral position due to natural variation in the degree of patient posterior/anterior tilt, initial patient mal-positioning and intra-operative forces.²⁷⁻²⁸ Furthermore, as the pelvis is concealed during surgery, the true orientation of the pelvis intra-operatively may be unknown by the orthopaedic surgeon. During THR surgery, if the pelvis is non-neutral, the angle the introducer makes with the theatre floor is not the same as the angle it makes with the sagittal pelvic plane (Figure 1.18). Consequently, the use of external landmark approaches may result in the acetabular component being placed at unknown angles relative to the intra-operative pelvis and deviation from target orientations will only become apparent during post-operative radiographic assessment.

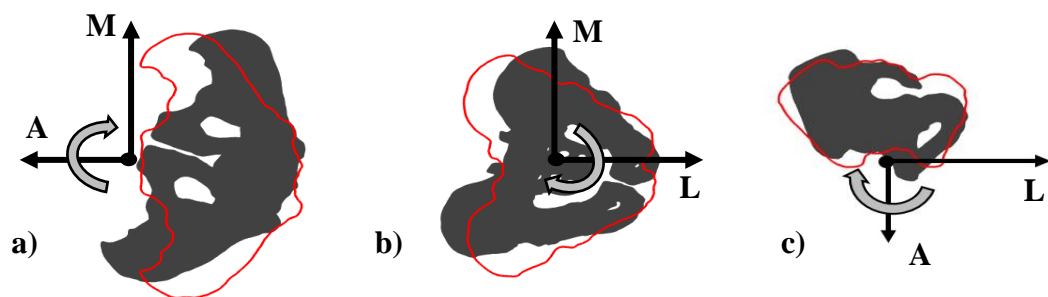


Figure 1.17 Elemental pelvic rotations for a left operative hip. Neutral pelvic orientation outlined in red: a) external rotation about the longitudinal (L) axis b) adduction about the anterior-posterior (AP) axis c) posterior tilt about the medio-lateral (ML) axis.

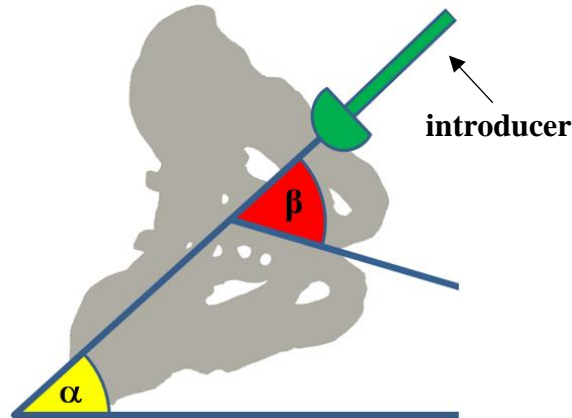


Figure 1.18 *If the pelvis has deviated from neutral, the angle of the introducer with the floor (α) is not the same as the angle it makes with the pelvic sagittal plane (β).*

1.11 Thesis Aim

Currently, a wide range of acetabular component orientations are observed on post-operative radiographs despite orthopaedic surgeons typically using fixed operative target angles.²⁹⁻³¹ Mal-orientation of the acetabular components can impede the longevity of the joint¹²⁻¹⁵ and thus reduce patient satisfaction. This thesis aimed to improve understanding of operative placement of acetabular components by explaining the discrepancy between operative and post-operative radiographic acetabular orientations. In particular, it sought to answer the question of how pelvic orientation affects acetabular cup orientation.



TWO

Literature Review

2.1 Total Hip Replacement Burden

Total Hip Replacements (THR) are used to reduce pain and increase mobility in patients suffering from osteoarthritis of the hip.³²⁻³⁴ It is a successful operation with current survivorship exceeding 90% at 10 years.³⁴ Despite this success, negative outcomes such as aseptic loosening and dislocation persist.¹ These negative outcomes may precede the need for a revision THR (re-operation following a primary THR).

With respect to THR, National Health Service hospitals receive payment per patient treated through a Payment by Results scheme.³⁵ The amount reimbursed is subject to national tariffs for each treatment pathway (surgical procedure, elective/non-elective, length of stay etc.). The cost of a primary THR in 2016 was £5,150.³⁵ Due to the presence of existing complications (need for removal of an existing THR), the cost of revision surgery is higher than the cost of primary THR (£7,150).³⁵ However, this represents the value reimbursed to hospital trusts based on a national average. For individual orthopaedic centres, each procedure may cost more or less than the national average. Vanhegan et al³⁶ reported an approximate loss of £860 (2010/11) per revision case for their hospital.

The volume of primary THR procedures performed within the United Kingdom (UK) per annum has undergone a steep percentage increase of 481% within the period 2003-2015 ($n_{2003} = 14,433$, $n_{2015} = 83,886$).¹ This increase in demand for primary THR procedures is not unique to the UK alone. The Swedish and Australian joint registries have also catalogued increasing levels of primary THR procedures per annum within the same period.³⁷⁻³⁸ Consequently, a rise in the number of revision THR procedures has also been observed.¹ As the average age of the UK population has been steadily

rising³⁹ (osteoarthritis is primarily an age-related disease), the burden of THR is set to increase.

In order to minimise the impact of the upcoming THR burden and its associated financial cost, it is important to identify surgical factors that can enhance patient satisfaction and reduce the need for expensive revision THR. Mal-orientation of the acetabular component is one such surgical factor that can impede the survivorship of a THR.¹²⁻¹⁵ Currently within the literature, a wide range of acetabular orientations are being reported post-operatively on radiographs.^{29-30,40-41} It is therefore important to ensure optimal acetabular positioning to help reduce the need for revision THR and thus lessen the THR burden.

2.2 Implications of acetabular mal-orientation

The orientation at which an acetabular component is implanted can affect the longevity of a THR.¹²⁻¹⁵ Complications resulting from mal-orientation of the acetabular component include impingement (Figure 2.1), dislocation and wear.^{12, 42-43}

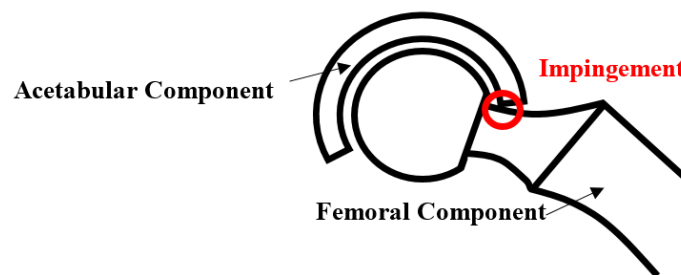


Figure 2.1 *Component-on-component impingement between the lip of the acetabular component and neck of the femoral component*

2.2.1 Impingement

Impingement occurs when two bodies come into contact with each other. With respect to THR, four types of impingement have been described: component-on-component

(CoC, Figure 2.1), bone-on-bone (BoB), component-on-bone (CoB) and soft-tissue impingement.⁴⁴⁻⁴⁶ Impingement between neighbouring hip structures can result from inadequate restoration of the hip joints normal range of motion (ROM).^{12,44}

Three planes have been used to describe the hip joints ROM: flexion / extension, abduction / adduction and internal / external rotation (Figure 1.8). In order to minimise the chance of impingement following a THR, it is important to replicate as close as possible, the hip joints normal ROM (Figure 1.8).^{8,47-53} Although global values for normal hip joint ROM have been described, the normal range may vary on a case by case basis. Both age and gender have been implicated as factors that alter the allowable range of normal hip motion.⁵¹⁻⁵²

2.2.1.1 Component-on-Component Impingement

Impingement between the neck of the femoral component and the lip of the acetabular component is classified as CoC impingement (Figure 2.1).⁴⁴⁻⁴⁵ The direction of acetabular component mal-orientation has been geometrically shown to impact the risk and direction of CoC impingement (anterior or posterior, Figure 2.2)^{12,15,54-55}

With respect to CoC impingement avoidance, optimal acetabular component orientation is a balancing act dictated by the different combinations of hip motions required for activities of daily living.^{15,57-60} For example, during normal walking gait, the hip becomes extended during the stance phase and flexed during the swing phase (Figure 2.3).⁶¹ These motions require contradictory acetabular component orientations to optimise their range of motion and thus a compromise for optimal acetabular component orientation is needed (Figure 2.2). Through a computational study, Ezquerro et al⁵⁴ has previously recommended a compromise for optimal acetabular orientation. Ezquerro et al⁵⁴ investigated the impact of acetabular orientation on the

achievable degree of hip internal / external rotation from two starting positions: hip extension in standing and hip flexion in sitting. A radiographic inclination between 40° to 60° and a radiographic anteversion between 15° to 25° was recommended.

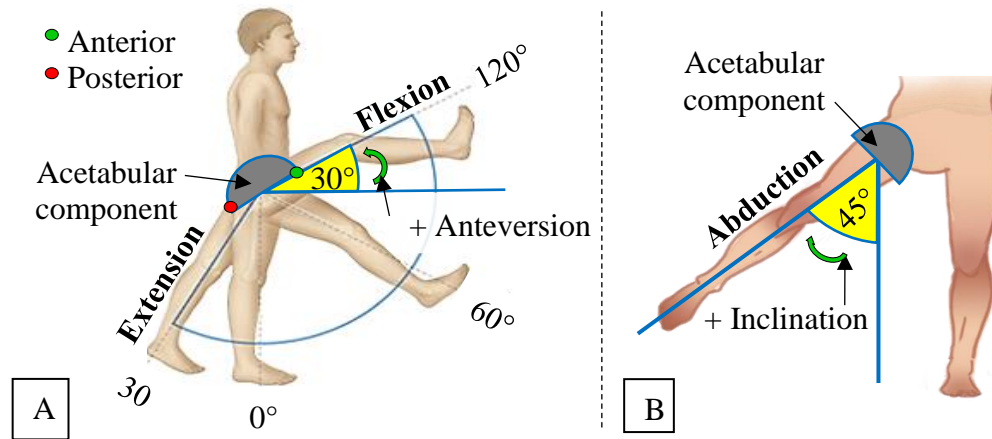


Figure 2.2 A) An increase in acetabular component anteversion increases allowable hip flexion whilst reducing allowable hip extension increasing the risk of posterior CoC impingement B) An increase in acetabular component inclination increases allowable hip abduction whilst reducing allowable hip adduction⁵⁶

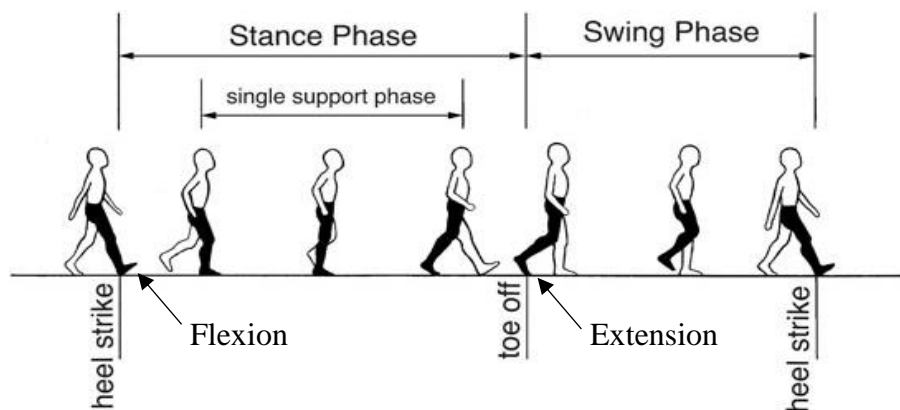


Figure 2.3 Stance and swing phase of normal gait. Hip extension occurs during stance phase and hip flexion occurs during swing phase.⁶²

A limitation of the safe-zone recommended by Ezquerro et al⁵⁴ is that it does not take into account the impact of femoral component anteversion (Figure 2.4). Combined

anteversion is typically regarded as the sum of femoral and acetabular anteversion.⁶³⁻
⁶⁴ However, more complex definitions have appeared within the literature. Widmer et al⁶⁵ defined combined anteversion as the sum of radiographic cup anteversion and 0.7 times the femoral anteversion based on the findings of a geometrical model.

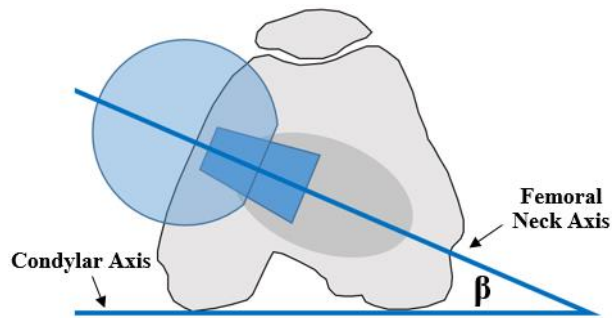


Figure 2.4 Femoral component Ante-version “β”

Widmer et al⁶⁵ proposed a safe target combined anteversion of 37° to minimise the risk of CoC impingement. However, in a clinical study by Fukunishi et al⁶⁴, only 77.2% (n=61/79) of their cohort fell within 10° of the 37° target proposed by Widmer et al. One factor that may have impeded the volume of joints that were classified as safe in the study by Fukunishi et al, was their use of cementless femoral stems alongside a limited target range (20°-25°) for intra-operative acetabular anteversion. Adjustment of femoral anteversion is only optional when using cemented femoral stems. For stability with a cementless femoral stem, motion between the stem and canal must be minimised to promote bony ingrowth.⁶⁶ This is achieved by press-fitting a slightly oversized femoral stem within the medullary canal. This causes the orientation of a cementless femoral stem to be guided by the native geometry of the medullary canal, reducing the control that orthopaedic surgeons have over femoral version compared with their undersized, cemented counterparts. As control over cementless femoral stem version is limited, a greater and more anatomic range of acetabular versions may have increased the volume of joints classified as being safe in

the clinical study completed by Fukunishi et al⁶⁴. This was confirmed in a later study by Fukunishi et al.⁶⁷ They were now able to place 92.3% (n=48/52) of their joints within an even smaller target range for combined anteversion ($37\pm5^\circ$). In this instance, target operative acetabular version was determined using Widmer's⁶⁵ definition of combined anteversion. To minimise CoC impingement, choice of acetabular anteversion should incorporate the anteversion of the femoral component. An increase in femoral component anteversion should be balanced with a decrease in acetabular component anteversion and vice versa.

During THR, the acetabular component is rigidly attached to the pelvis. The pelvis is a dynamic object which changes orientation during different activities of daily living.⁶⁸⁻⁷⁰ Consequently the acetabular component will have different functional orientations for different activities of daily living. Typically, in the absence of comorbidities, the pelvis tilts anteriorly when going from a seated to a standing position (Figure 2.5).^{68,70-71} Rising from a seated position (increased anterior pelvic tilt) reduces the functional anteversion of the acetabular component (Figure 2.5).⁷² If the degree of anteversion at which the acetabular component was implanted relative to the pelvis was initially insufficient, a greater loss of functional acetabular component anteversion will be observed during this transition between sitting and standing. This pre-disposes the joint to a reduced range of hip flexion, increasing the chance for anterior CoC impingement during this manoeuvre. This is further complicated by natural variation in pelvic tilt which changes between patients for a given manoeuvre.^{68,71-72} The use of the safe zone recommended by Ezquerro et al⁵⁴ does not account for the variation in pelvic tilt between manoeuvres and between patients. The risk of CoC impingement due to a mal-orientated acetabular component is subject to

the direction of acetabular component mal-orientation, a patient's native pelvic kinematics, and the type of activity being performed.

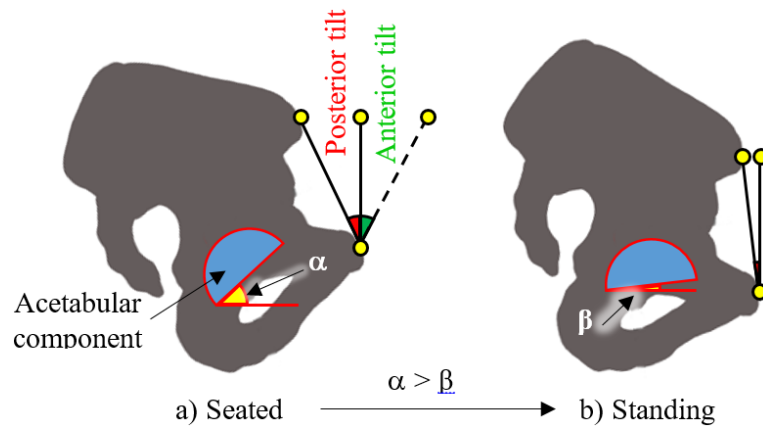


Figure 2.5 As a healthy subject rises from a a) seated to a b) standing position, the degree of posterior pelvic tilt and anteversion decreases ($\alpha > \beta$).

For a healthy subject, adaption of pelvic tilt between sitting and standing is compensated for by changes in the spinal lumbar region; the spinopelvic balance.⁷³⁻⁷⁴ However, comorbidities such as spinal fusion can restrict spinal movement.⁷³⁻⁷⁴ Consequently, the allowable change in pelvic tilt will also be reduced. Typically, in the absence of comorbidities, the pelvis has a greater degree of posterior pelvic tilt in sitting than in standing.^{68,70-71} However, if the spinopelvic balance has been impacted, the pelvis can tilt anteriorly whilst sitting; the patient will sit as if they are standing.⁷⁴ Anterior pelvic tilt reduces the anteversion of the acetabular component which increases the probability of anterior CoC impingement in sitting. Conversely, whilst standing, excessive posterior pelvic tilt has also been observed; the patient will stand as if they are sitting.⁷⁴ This increases the anteversion of the acetabular component, which reduces the allowable extension of the hip joint; an increased probability of posterior CoC impingement in standing. An appropriate choice of acetabular component orientation should reflect the spinopelvic balance of the patient.

The geometry of the implanted prosthetic components alongside acetabular component mal-orientation influences the risk of CoC impingement. The modal choice of femoral component diameter within the UK is 32 mm (46%, n=41790 / 91843, 2016); mean native femoral head diameter is 46.1 mm.⁷⁵⁻⁷⁶ This represents a loss of bearing diameter following a THR; the head of the implanted femoral component is smaller than the native bony femoral head. A loss of bearing diameter reduces the sliding distance for a given angular ROM (Figure 2.6) and can increase the risk of impingement if an appropriate head to neck ratio (relative diameters of the head and neck of the femoral component) is not employed.⁷⁷⁻⁸⁰

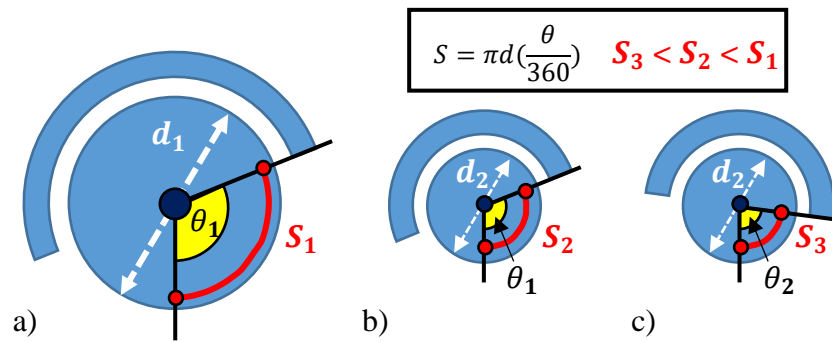


Figure 2.6 A loss of bearing diameter (d) and ROM (θ) due to a mal-orientated acetabular component leads to a reduced sliding distance (S) prior to CoC impingement: a) Optimal bearing size and acetabular component orientation, b) Loss of bearing diameter, c) Loss of bearing diameter and ROM due to a mal-orientated acetabular component.

To compound this problem, if the implanted acetabular component is mal-orientated, there will be a loss of hip ROM which will further reduce the bearing sliding distance (Figure 2.6) to impingement. The maximum bearing diameter which can be implanted may be limited by the minimum thickness required for the acetabular liner⁸¹⁻⁸² and by the native geometry of the hip joint (females have smaller native femoral head diameters than males⁸³⁻⁸⁵). Mal-orientation of the acetabular component coupled with

a smaller bearing diameter (a small head-neck ratio) increases the likelihood of CoC impingement.^{44,86}

Another geometrical factor that influences CoC impingement alongside acetabular component mal-orientation is the presence of an elevated rim on the posterior aspect of the acetabular component (Figure 2.7). The purpose of an elevated rim is to prevent the head of the femoral component from escaping through the posterior aspect of the acetabular component following anterior CoC impingement.

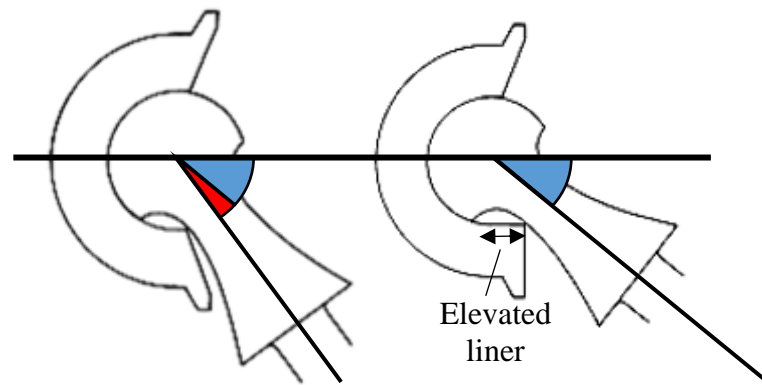


Figure 2.7 The hip ROM prior to posterior impingement available to an elevated liner (blue) is less than that available to a normal liner (red & blue) when the acetabular component is excessively anteverted.⁸⁷

Acetabular components with an elevated liner have been clinically associated with a greater chance of CoC impingement compared with their normal counterparts.⁷⁹ This increased probability of CoC impingement when using elevated rims results from a reduced range of motion prior to posterior CoC impingement.⁸⁷ The allowable hip ROM when using an elevated liner will be further compromised if the acetabular component is mal-orientated. For example, excessive anteversion of the acetabular component will result in earlier posterior CoC impingement for an elevated liner when compared to a normal liner.

2.2.1.2 Bone-on-Bone Impingement

Geometrical models of the prosthetic components alone do not account for all impingement events during a hips ROM; they fail to take into account the bony structures surrounding the prosthetic components.^{12, 15, 54-55} Geometrical models that incorporate the bony geometry of the femur and pelvis have illustrated that BoB impingement (Figure 2.8) can precede CoC impingement.⁸⁸⁻⁹²

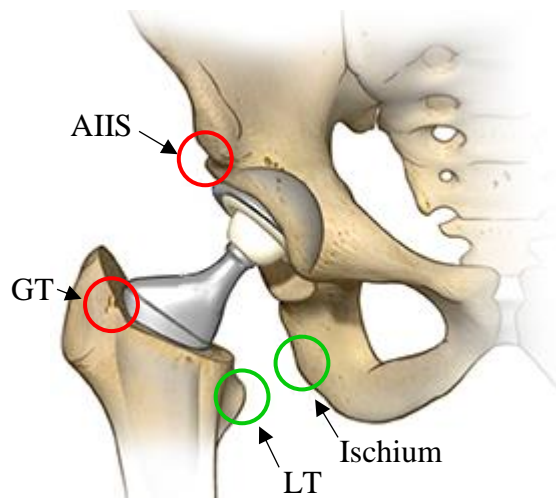


Figure 2.8 Anterior BoB impingement between the anterior greater trochanteric (GT) region of the femur and the anterior inferior iliac spine (AIIS) can occur during flexion and internal rotation of the hip joint (red). Posterior BoB impingement between the lesser trochanter (LT) and the ischium of the pelvis can occur during external rotation (green).⁹³

Variation in bony morphology between patients has been shown to influence the hip ROM prior to BoB impingement.⁸⁸⁻⁸⁹ An increase in the scale of pelvic and femur geometry has been associated with a loss of hip flexion and internal / external rotation prior to BoB impingement.⁸⁸⁻⁸⁹ The site of BoB impingement may be anterior (during flexion and internal rotation) or posterior (during external rotation, Figure 2.8).⁸⁸⁻⁸⁹ Impingement between bony surfaces is associated with post-operative pain.⁹⁴⁻⁹⁵

In order to minimise the risk of BoB impingement due to bony morphology and thus post-operative pain, it is important to maintain the pre-operative spacing between the bony femur and pelvis.^{76,95-96} Traditionally, when preparing the acetabulum, orthopaedic surgeons have reamed down to the true acetabulum floor. Bonnin et al²⁰ illustrated that the distance between the native acetabular floor and what is referred to as the true floor (acetabular offset, Figure 1.14) varies between patients (Figure 2.9). Consequently, if an orthopaedic surgeon reams down to the true acetabular floor, there will be a loss of acetabular offset; 10mm of acetabular offset will be lost in 18% of male patients.²⁰

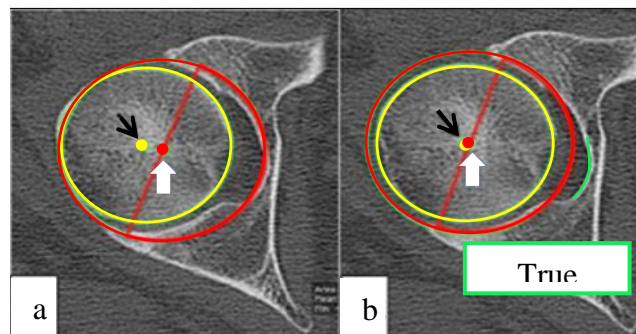


Figure 2.9 Native femoral head centre (yellow) is marked with a black arrow. Reconstructed hip joint centre (red) is marked with a white arrow a) Acetabular offset is reduced when the cup is positioned flush to the true floor b) Acetabular offset is restored using conservative reaming²⁰

Therefore, a surgeon reaming down to the true floor needs to compensate for this loss of acetabular offset by increasing femoral offset (Figure 1.14), if they want to restore global offset. In this scenario, to restore global offset and thus the spacing between the bony pelvis and femur, a femoral component with an increased neck length should be used. This increases the femoral offset of the prosthetic hip joint when compared to the native geometry of the bony femur but restores global offset (Figure 2.10). An

increase in neck length has been associated with an increased range of motion prior to BoB impingement.⁹⁷

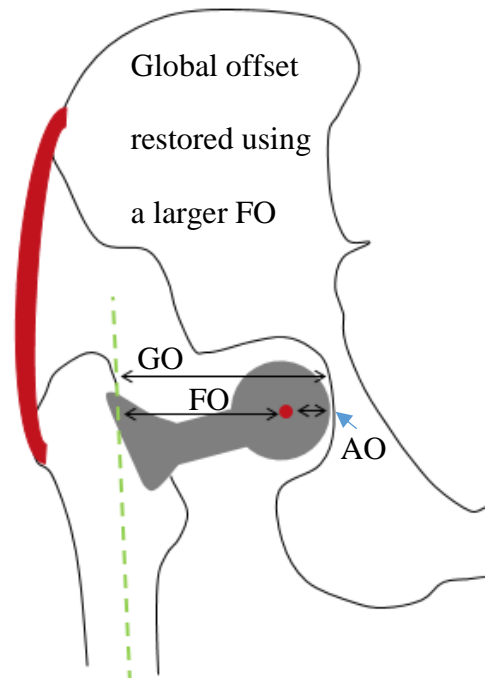


Figure 2.10 An increase in femoral offset (FO) may be used to restore global offset (GO) following a loss of acetabular offset (AO) due to reaming.

Although a change in global offset has been indicated as a factor pertaining to BoB impingement, geometrical bony models have observed BoB impingement in the presence of a restored global offset.⁹⁰⁻⁹¹ Thus global offset alone is not accountable for BoB impingement. High acetabular component inclination ($>50^\circ$) and version ($>28^\circ$) have been associated with BoB impingement during flexion.⁹⁰⁻⁹¹ With respect to these models, BoB impingement occurred on or after 120° of hip flexion; a peak value of flexion for normal hip ROM (Figure 1.8).⁹⁰⁻⁹¹ Consequently, although high inclination and anteversion can result in BoB impingement, it is unlikely to occur until the extremes of normal hip joint flexion.

The propensity for BoB impingement has been associated with the direction of hip motion.⁹² Kessler et al⁹² developed a bony geometrical model that independently analysed the influence of each of the different hip motions on BoB impingement. From this, they illustrated that BoB impingement was more likely to occur during leg abduction than during leg flexion for a given set of acetabular component orientations. However, a limitation of this model, is that it did not consider the ROM required for a normal hip joint to function. Although a greater volume of BoB impingements were observed during abduction for a given set of acetabular component orientations, the abduction ROM until BoB impingement tended to exceed 45° i.e. the abduction ROM exceeded that required for a normal hip joint to function. Conversely, for the same set of acetabular component orientations, the flexion ROM until BoB impingement tended to be less than 120°, i.e. the flexion ROM was less than that required for a normal hip joint to function. Thus, when viewed with respect to a normal hip joint's ROM, Kessler et al's⁹² results indicate a higher likelihood of BoB impingement due to flexion. Similar to the previous studies, Kessler et al⁹² associated BoB impingement during flexion with a highly anteverted acetabular component. In the presence of a restored global offset, optimal acetabular orientation is required to reduce BoB impingement at the extremes of hip flexion.

As discussed previously, the use of large bearing diameters can help reduce the impact of a mal-orientated acetabular component by increasing the sliding distance prior to CoC impingement (Figure 2.6) for a given head to neck ratio. However, if the sliding distance is sufficiently large and an adequate head to neck ratio is not employed, the extremes of normal hip ROM can be reached; an increased likelihood of BoB impingement will result.^{44,86,90} Optimal acetabular component orientation, an

appropriate choice of bearing diameter and an adequate head to neck ratio are required to obtain the balance between CoC and BoB impingement.

2.2.1.3 Component-on-Bone Impingement

If the orientation of the implanted acetabular component does not match the orientation of the native acetabulum, the rim of the acetabular component will not be co-planar with the rim of the native bony acetabulum. Insufficient anteversion will result in posterior protrusion of the native bony acetabular rim below the rim of the acetabular component.⁵³ This increases the probability of posterior impingement between the neck of the femoral component and the rim of the bony acetabulum during hip extension (Figure 2.11).

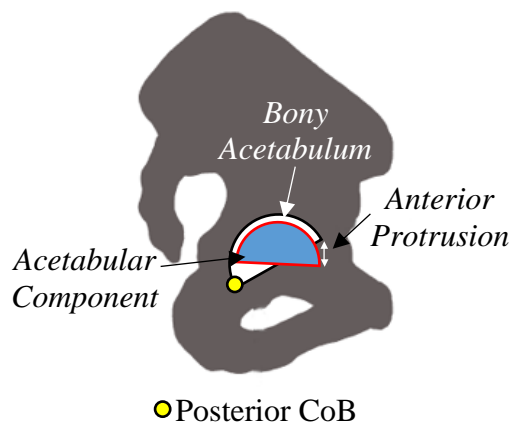


Figure 2.11 Anterior protrusion of the acetabular component below the native bony acetabulum. Posterior component-on-bone (CoB) impingement between the neck of the femoral component and the posterior aspect of the native bony acetabulum will occur prior to component-on-component impingement.

This concept was confirmed by a geometrical model developed by Cinotti et al.⁹⁰ They associated CoB impingement with a loss of acetabular component anteversion during hip extension.⁹⁰ A limitation of their study was that they used pelvic and femur geometry from a single subject. Differences in bony morphology across a population

may alter the direction and likelihood of CoB impingement following a mal-orientated THR. For example, the presence of osteophytes (bony spurs) which can extend the anterior aspect of the bony acetabulum may also induce anterior CoB impingement.⁹⁸ To avoid CoB impingement, the orientation of the acetabular component should match the native orientation of the bony acetabulum. In practice, the native orientation of the bony acetabulum may be hard to judge due to the presence of bony osteophytes.

2.2.1.4 Soft tissue impingement

As previously described, when the acetabular component is placed in a retroverted position, anterior protrusion of the acetabular component below the native bony acetabulum can occur (Figure 2.11). Clinically, this has been associated with groin pain following a THR due to anterior impingement between the rim of the acetabular component and the iliopsoas tendon.^{46,99-100} Additional treatment is required following a diagnosis of iliopsoas impingement to relieve the patients symptoms of pain: conservative management, tenotomy, or revision of the acetabular component.^{46,101} The choice of treatment may reflect the degree of acetabular component mal-orientation. Chalmers et al¹⁰¹ associated more effective pain relief for iliopsoas impingement using acetabular component revision if the anterior protrusion of the acetabular component exceeded 8 mm; iliopsoas release (tenotomy) was recommended for patients with less than 8 mm of anterior protrusion. To avoid iliopsoas impingement, excessive anterior protrusion should be avoided by aligning the rim of the acetabular component with the rim of the native bony acetabulum.

Impingement between the posterior aspect of the acetabular component and the obturator externus has also been observed. In a study carried out by Muller et al¹⁰², an increased likelihood of obturator externus impingement was associated with a greater

angle of acetabular component inclination. Although obturator externus impingement was frequently observed in their study, it rarely proceeded to a painful hip post-operatively. Consequently, although obturator externus impingement is of little clinical significance, its risk can be managed by using conservative angles of acetabular inclination (radiographic inclination of $40^{\circ} \pm 5.4^{\circ}$).¹⁰²

2.2.2 Dislocation

When the head of the femoral component completely escapes the confines of the acetabular component, a dislocation has occurred (Figure 2.12).¹⁰³ Between 0.3% and 10% of patients will experience a dislocation following a primary THR.^{29,42,103-105} To compound this problem, patients who have experienced an initial dislocation are more prone to recurrent dislocations.^{42,106} Corrective intervention is required to treat a dislocation event.¹⁰⁷ Dislocation events impede patient satisfaction and incur higher costs due to the need for additional treatment.

The mechanism of dislocation induced by CoC impingement has been described using an experimentally validated Finite Element Analysis (FEA) model developed by Sciferet et al.¹⁰⁸ The experimental rig used to validate the FEA model was set up such that it drove rotation of an acetabular component about the head of a femoral component until CoC impingement and subsequent dislocation. This model demonstrated, that when CoC impingement occurs, a new pivot is introduced at the point of contact between the neck of the femoral component and lip of the acetabular component. As CoC impingement progresses, the region of contact between the bearing surfaces (inner spherical surface of acetabular component and head of the femoral component) shifts toward the acetabular component lip opposing the site of CoC impingement (egress site). The movement of the region of contact between the

bearing surfaces is opposed by a resistive moment produced by the liner of the acetabular component. This resistive moment emerges as a result of tangential stress and friction due to the hip joint force and leg rotation. If the external loading situation (musculature) that led to impingement overcomes the resistive moment produced by the acetabular component, complete dislocation is achievable; the region of contact between bearing surfaces escapes the confines of the acetabular component.



Figure 2.12 Hip joint dislocation following a THR. The femoral head has escaped the confines of the acetabular component.¹⁰³

Sciferet et al¹⁰⁸ illustrated that the magnitude of the resistive moment generated by the liner of the acetabular component changes throughout the dislocation procedure (Figure 2.13). Prior to CoC impingement, the acetabular component exerts a relatively low resistive moment to the motion of the femoral head. Following CoC impingement, there is a steep increase in the magnitude of the resistive moment generated by the acetabular component until a peak value is obtained. If the external loading situation (musculature) exceeds the peak resistive moment, subluxation (partial dislocation) begins. During subluxation the resistive moment provided by the acetabular component declines as the bearing contact area decreases until complete dislocation (Figure 2.13). Scifert et al¹⁰⁸ illustrated that subluxation extends the hips allowable ROM beyond that required for CoC impingement (Figure 2.13). Impingement models

that rely on the geometry of the components alone without kinematics to detect the hips allowable ROM are limited.

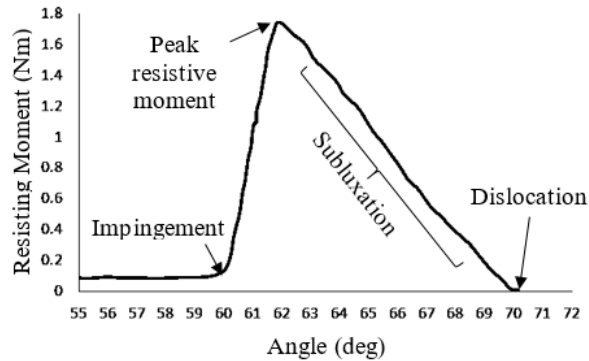


Figure 2.13 Resistive moments over the course of a dislocation¹⁰⁸

A limitation of the model developed by Scifert et al¹⁰⁸ is that the experimental jig used to validate it only allowed a single degree of freedom: a single hip motion. In practice, activities of daily living require more complex motions which utilise combinations of each of the 3 types of hip motion. To account for this, newer FEA models incorporate kinematics captured from activities of daily living.^{15,54-55,86,109-110} As posterior dislocation is clinically more probable than anterior dislocation¹¹¹, FEA models have primarily focused on activities that are prone to posterior dislocation: erectly seated leg-crossing and shoe tying.^{54-55,86,110} These studies have associated increased acetabular component inclination or anteversion with a higher peak resisting moment, a reduced chance of anterior CoC impingement and thus a reduced risk of posterior dislocation.^{54-55,86,110}

Although dislocation induced by CoC impingement is the primary mode of dislocation, two other mechanisms have been described via experimental and computational studies (Figure 2.14): (1) dislocation induced by BoB impingement and (2) spontaneous dislocation without impingement.^{86,112-114}

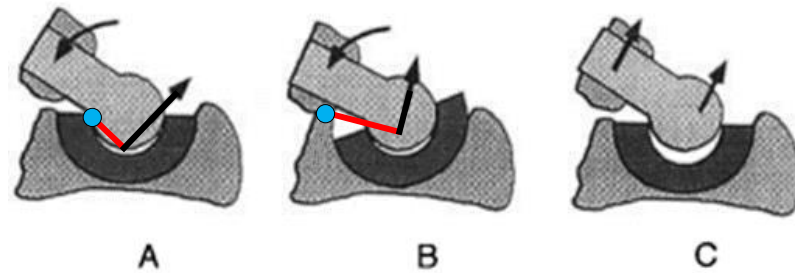


Figure 2.14 Resistive moment arm (red) resulting from a) CoC induced dislocation and b) BoB induced dislocation. BoB induced dislocation results in a greater resistive moment arm. c) Shear separation of the head of the femoral component from the acetabular component.¹¹²

Dislocation induced by BoB impingement is less common as it results in higher resistive moments than that which would arise due to CoC impingement; BoB impingement increases the resistive moment lever arm (Figure 2.14).¹¹² As previously discussed, mal-orientation of the acetabular component can induce BoB impingement and thus dislocation due to BoB impingement. The final mode (albeit infrequent) is spontaneous dislocation without impingement.^{86,112-114} Spontaneous dislocation occurs when the head of the femoral component separates from the acetabular component via a shearing action. It is believed to be the result of muscle traction or external forces.¹¹³⁻¹¹⁴ Spontaneous dislocation has been computationally associated with the leg crossing manoeuvre whilst sitting, acetabular component anteversion ($>10^\circ$) and inclination ($>45^\circ$).^{86,113}

Dislocation and its association with acetabular component orientation have been clinically investigated. Traditionally, orthopaedic surgeons have aimed for the Lewinnek safe zones¹¹⁵ when orientating the acetabular component. The Lewinnek safe zone recommends $40 \pm 10^\circ$ of radiographic inclination and $15 \pm 10^\circ$ of radiographic version to avoid clinical dislocation. However, the validity of this safe zone has been

called into question. A limiting factor of the Lewinnek safe zone is that it was based on the findings of only nine dislocations. Larger clinical studies by Biedermann et al⁴², Danoff et al,²⁹ and Abdel et al³⁰ have revealed high incidences of dislocations within the Lewinnek safe zone: 60% (n=76/127 dislocations), 47% (n=20/42 dislocations) and 58% (n=120/206 dislocations) respectfully. Furthermore, placement of the acetabular component within the Lewinnek safe zone has not been proven to guarantee improved functional outcome (e.g. pain and/or range of motion).⁴⁰

Alternate safe zones have been proposed to minimise the risk of dislocation based on the findings of clinical studies. Danoff et al²⁹ proposed the use of a circular safe zone centred at 41.4° of radiographic inclination and 17.1° of radiographic version with a radius of 4.3°. Mellon et al¹⁴ found an optimum safe zone of placement when a mean radiographic inclination of 39.7° ($\pm 6.6^\circ$) and a mean radiographic version of 14.9° ($\pm 9.0^\circ$) was achieved. In this instance, the safe zone highlighted was also associated with a reduced risk of impingement and edge loading. Grammatopoulos et al⁴⁰ found a reduced rate of dislocation when using 40° \pm 15° of radiographic inclination and 15° \pm 15° of radiographic version, i.e. an enlarged Lewinnek safe zone. However, in the same paper, Grammatopoulos et al⁴⁰ went on to define a different and smaller safe zone for improved functional outcomes, a radiographic inclination of 45 \pm 5° and radiographic version of 25 \pm 5°. It is apparent, that a consensus does not exist within the literature regarding a safe zone for optimum placement of the acetabular component to avoid dislocation.

A “one size fits all approach” to avoid dislocation and, thus, the use of safe zones may not be applicable due to the variation in the native bony acetabulum orientation. Goudie et al¹¹⁶ discovered that 75% of their cohort (n=49/65) had native acetabulum

orientations outside of the Lewinnek safe zone. Additionally, there was a significant difference in the extent of acetabular radiographic version between males and females. Both conclusions were supported by the findings of Murtha et al.¹¹⁷ Merle et al¹¹⁸ found that only 15% (n=19) of their cohort's native acetabula fell within the Lewinnek zone for radiographic inclination. Conversely, they found that their native versions typically matched (95%, n=125) the recommended safe zone for radiographic version proposed by Lewinnek et al. This agreement with the Lewinnek safe zone for radiographic version by Merle et al¹¹⁸ may result from regional differences in native bony geometry. The native orientation of the acetabulum should be considered to avoid impingement and subsequent dislocation events.

With respect to combined anteversion, Jolles et al⁶³ clinically identified that the risk of dislocation was 6.9 times smaller if the combined anteversion was between 40° and 60°. Similarly, Nakashima et al¹¹⁹ also observed a reduced risk of clinical dislocation within the same range of combined anteversion. Combined anteversion is an important factor for reducing the risk of impingement and subsequent dislocation.

Patient obesity has been clinically shown to increase the risk of dislocation.¹²⁰⁻¹²² Spontaneous dislocation due to external loading from thigh-on-thigh contact has been computationally described as a possible mechanism of obesity induced dislocation (Figure 2.15).¹¹⁴ During hip flexion and adduction, a lateral external force can act on the head of the femoral component due to thigh-on-thigh contact. This lateral force can laterally push the head of the femoral component from the acetabular component if the acetabular component is excessively inclined. Patients who are morbidly obese (BMI >40) are of particular concern. Acetabular component orientation should thus be

considered alongside patient comorbidities such as obesity to minimise the risk of dislocation.

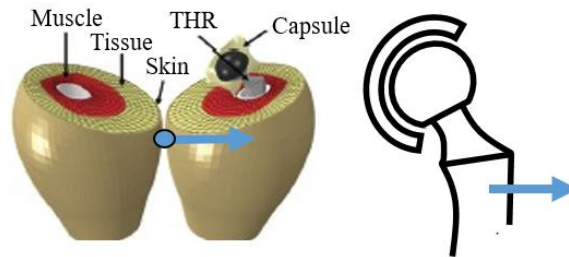


Figure 2.15 Lateral forces from thigh-on-thigh contact can result in lateral separation of the femoral head from the acetabular component¹¹⁴

2.2.3 Wear

Acetabular component wear is a recurrent problem, as indicated by the large volume of retrieved acetabular components that have shown signs of deformity (between 27% and 56%).^{78-79,123-125} Factors that have been related to wear are edge-loading, prosthetic geometry, containment, and bearing material combinations.

2.2.3.1 Edge-Loading

Edge-loading at the rim of the acetabular component can follow impingement (Figure 2.16); elevated contact stresses have been computationally demonstrated at both the impingement and egress sites.^{54,86,108,111,126} These contact stresses can exceed the yield strength^{54, 86, 127} of the acetabular liner resulting in permanent deformation and the production of third body wear debris. In addition to encouraging further accumulation of wear, through secondary wear mechanisms such as abrasion and adhesion, wear debris has been linked to osteolysis (destruction of surrounding bone tissue)¹²⁸⁻¹²⁹ resulting from an immune response to the presence of third body particles. Such bone resorption around the prosthetic bone interface can result in aseptic loosening of the implant components.¹³⁰ Although dislocation events primarily occur within the first

three post-operative months, excessive wear can lead to dislocation in the long term¹⁰⁵, in addition to a loss of bearing surface and consequently hip ROM.

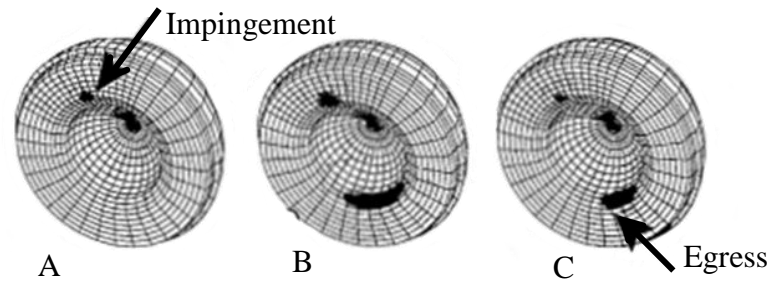


Figure 2.16 A) Contact stress immediately after impingement, B) following impingement but prior to subluxation and C) following subluxation.¹⁰⁸

Elkins et al¹³¹ developed a computational model that incorporated an impingement stability metric (femoral head subluxation distance) and a volumetric wear metric for investigating the impact of acetabular orientation. The model incorporated different motion challenges (n=5) to account for both anterior (e.g. pivot) and posterior (e.g. sit to stand) stability challenges. Elkins et al¹³¹ reported a trade-off between optimising stability and reducing wear (Figure 2.17).

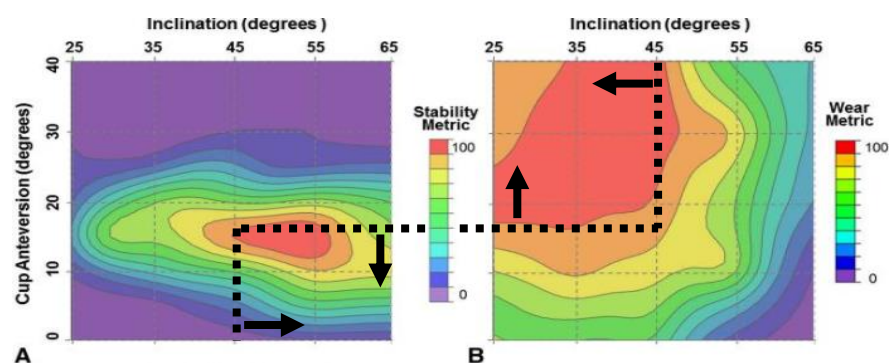


Figure 2.17 A) Stability and B) Wear metric plots against acetabular orientation.

Optimum acetabular orientation (black) is a trade-off between stability and wear.¹³¹

Stability was approximately optimised for angles of anatomic inclination greater than 45° and angles of anatomic anteversion less than 17° . Conversely, the opposite was true for wear. To account for the combined effects of wear and stability, Elkins et al¹³¹ recommended an ideal anatomic cup orientation of $46^\circ \pm 12^\circ$ inclination and $15^\circ \pm 4^\circ$ anteversion.

Edge-loading (at the rim of the acetabular component) as previously described, can result from CoC impingement. However, disruption of fluid film dynamics can also result in edge-loading.¹³² Under ideal conditions, synovial fluid (lubricant) is drawn between the bearing surfaces via a hydrodynamic effect; fluid is drawn in due to the relative motion of bearing surfaces.¹³³ However, if the acetabular component is excessively inclined, the distance between the rim of the acetabular component and the line of action of the hip joint force is reduced (Figure 2.18). This moves the peak contact pressure towards the rim of the acetabular component.¹³⁵

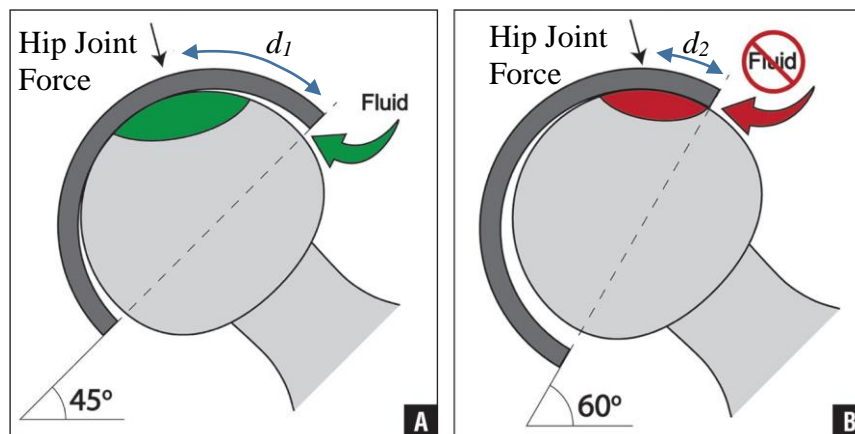


Figure 2.18 Distance between the line of action of the hip joint force and the edge of the acetabular rim (d_i) decreases with increasing acetabular inclination. Increased contact pressure at the rim of the acetabular components disrupts the flow of lubrication into the joint.¹³⁴

An increase in contact pressure at the rim of the acetabular component disrupts the flow of lubrication into the prosthetic joint such that direct contact between bearing surfaces can occur. This can result in a higher level of prosthetic component wear as demonstrated by retrieval and hip joint simulator studies.^{43,136-137} Micro-separation (occurs regularly during gait¹³⁸⁻¹³⁹) between the femoral head centre and the hip joint centre is an aggregating factor. Highly inclined acetabular components ($>55^\circ$ operative inclination) within bearings experiencing micro-separation have been found to experience higher levels of wear.^{43,137} In addition to wear, for hard-on-hard bearings, edge-loading due to excessive inclination has also been associated with audible squeaking of the joint.¹⁴⁰⁻¹⁴¹

Restoration of global hip height is required to minimise the risk of a leg length discrepancy post-operatively and thus a change in functional acetabular inclination (Figure 1.14).¹⁴² Alternatively, the presence of deformities such as pelvic obliquity (fixed pelvic adduction) or inadequate neck resection during THR may also influence the functional inclination of the acetabular component (Figure 2.19).^{142,145}

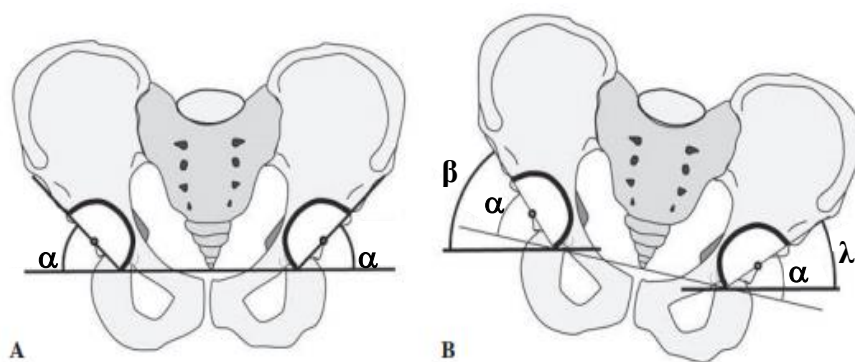


Figure 2.19 A) Acetabular component implanted with an inclination of α relative to a pelvis without fixed pelvic deformities. B) Fixed pelvic deformities (pelvic obliquity) or leg length discrepancies can increase the functional inclination (β) of the joint ($\beta > \alpha$)¹⁴⁶

Inadequate neck resection restricts the placement of the femoral components which can result in a long limb post-operatively.¹⁴² The hip joint force and resulting contact pressure at the rim for a highly inclined acetabular component will be elevated for a person with a higher BMI. Orthopaedic surgeons therefore often aim to restore the global position of the hip joint to account for natural deformities and minimise the risk of excessive inclination, edge-loading, and increased component wear, particularly in patients with high BMIs.¹⁴⁷

2.2.3.2 Prosthetic geometry

A limitation of the safe zone for acetabular orientation proposed by Elkins et al¹³¹ is that the safe zone was proposed based on the use of a single head diameter (36mm) and a fixed femoral anteversion of 20°. As illustrated within their own model, changes in bearing diameter and femoral version resulted in the need for different acetabular orientations to optimise the ROM before instability and to reduce volumetric wear. An increase in femoral version and a loss of bearing diameter were associated with a need for higher anatomical angles of inclination. Conversely, an increase in femoral version and a loss of bearing diameter were associated with a need for lower angles of anatomical anteversion.

Although large bearing diameters may be used to compensate for a loss in hip ROM due to a mal-orientated acetabular component, they are not without their own risks. Archard's wear equation states that the volume of wear debris produced is proportional to the "sliding distance".¹⁴⁸ An increase in femoral head diameter and, consequently, the "sliding distance" has been shown to negatively impact the rate of volumetric wear of highly-crosslinked polyethylene acetabular liners¹⁴⁹⁻¹⁵⁰ (the most frequent choice of acetabular liner in the UK¹). Furthermore, volumetric constraints

imposed by the native bony acetabulum result in the use of thinner acetabular liners to compensate for large femoral heads. Studies have illustrated that the rate of wear increases as the thickness of the acetabular liner decreases.⁸¹⁻⁸²

In addition to bearing diameter, the lip radius of the acetabular component may impede the choice of optimal acetabular component orientation. Through a FEA analysis investigating a trunk leaning manoeuvre (e.g. tying shoes), Elkins et al¹¹⁰ demonstrated a complex relationship between acetabular orientation and the lip radii of the acetabular component. For a lip radius of 4 mm, the optimum radiographic acetabular orientation for minimising contact stress was 70° of inclination and 25° of version, an acetabular inclination that would seem in excess by any of the previously recommended safe-zones. However, within this study, only one manoeuvre was investigated. Additional manoeuvres may highlight the need for compromise with respect to acetabular orientation to reduce wear. The safe zone for optimal acetabular orientation is dynamic; it changes location subject to the prosthetic components employed.

2.2.3.3 Containment

Containment, the level of contact between the native acetabulum walls and the acetabular component is also affected by acetabular cup orientation. Good containment is required to equalise load distribution within the bony acetabulum and has been associated with reduced post-operative radiolucency around the acetabular component (i.e. less bone resorption), less backside acetabular component wear, and the decreased risk of aseptic loosening.^{45, 151-153}

2.2.3.4 Bearing Material

Additional negative consequences from mal-orientated cups can be specific to the bearing material employed. In order to reduce the impact of biological responses and further mechanical damage through third body wear, a good choice of bearing material should minimise the production of wear debris and would ideally be biologically inert.¹⁵⁴ Furthermore, articulating surfaces should have low coefficients of friction to reduce abrasive and adhesive wear.¹⁵⁴

Hard-on-Soft Bearing Combinations

Examples of hard-on-soft bearings include a metal or ceramic femoral head articulating within a polyethylene acetabular liner. A metal head within a polyethylene acetabular liner is the most commonly adopted bearing couple within the UK.¹ Polyethylene has been the primary material used to construct plastic acetabular liners since its introduction by Sir John Charnley in the 1960's.¹⁵⁵ Ultrahigh molecular weight polyethylene (UHMWPE) was adopted by Charnley due to the significant increase in wear resistance it displayed over polytetrafluoroethylene.¹⁵⁵⁻¹⁵⁶ Despite this dramatic improvement, a failing of UHMWPE remained the large wear rates associated with its use.¹⁵⁶⁻¹⁵⁹ Wear debris from UHMWPE has been indicated in inducing osteolysis and, consequently, aseptic loosening.¹²⁸⁻¹²⁹

In an effort to reduce the wear debris produced by UHMWPE, crosslinking of polyethylene has been introduced. Crosslinking is achieved through radiation and thermal treatment of the polyethylene acetabular liner.¹⁶⁰ Highly crosslinked polyethylene (XLPE) has been shown to reduce the amount of wear debris produced by up to 87% when compared to UHMWPE.¹⁵⁸⁻¹⁶¹ The use of ceramic in place of metal femoral heads has also been promoted. Ceramic femoral heads have a lower surface

roughness than their metal counterparts which has been shown to reduce volumetric wear by up to 50%.¹⁶² Recently, there has been a rise in the number of ceramic-on-plastic bearings used within the UK.¹

Hard-on-Hard Bearing Combinations

The volumetric wear produced by two articulating surfaces is inversely proportional to the hardness of the softest surface.¹⁴⁸ In an effort to minimise the volume of wear debris produced, hard-on-hard surfaces such as metal-on-metal or ceramic-on-ceramic have been used. Theoretically, the use of metal-on-metal bearings have been shown to reduce wear rates when compared to bearings containing XLPE acetabular liners.¹⁶³ The volume of wear debris produced is further reduced if ceramic-on-ceramic bearings are adopted.¹⁶³⁻¹⁶⁴

However, wear particulates from metal-on-metal bearings have been shown to induce severe soft tissue reactions.¹⁶⁵ As a consequence, the use of metal-on-metal bearings, which had previously been very popular within the UK, has nearly been completely abandoned.¹ Unlike of metal-on-metal bearings, ceramic pairings exhibit a low risk for adverse soft tissue reaction because any wear debris produced is biologically inert. However, ceramic-on-ceramic bearings have a lower fracture toughness than their metal-on-metal or metal-on-plastic equivalents.¹⁶⁶⁻¹⁶⁷ Regardless, a low frequency of failure due to fracture is apparent in the current generation of ceramics.¹⁶⁸ An additional negative side effect of all hard-on-hard bearings, including ceramic-on-ceramic, is their tendency to sometimes produce audible squeaks during gait.¹⁴⁰⁻¹⁴¹

2.3 Navigation

Acetabular component orientations *between* orthopaedic centres may vary subject to differences in the choice of acetabular safe-zone. Furthermore, outliers frequently

occur *within* orthopaedic centres for a given safe-zone.²⁹⁻³¹ Although surgical navigation aims to control component placement, choice of navigation may impede an orthopaedic surgeon's ability to achieve their target acetabular orientation.

Saxler et al¹⁶⁹ illustrated the potential inaccuracy of the freehand approach (Figure 1.15) with only 25.7% (n=27/105) of their cohort being placed within the Lewinnek safe zone. In contrast, Bosker et al¹⁷⁰ were able to place 70.5% (n=141/200) of their cohort within the Lewinnek safe zone when using a freehand approach. Thus, differences in experience across orthopaedic centres or between orthopaedic surgeons can contribute to surgical inaccuracy.¹⁷⁰

As demonstrated by Grammatopoulos et al,¹⁷¹ the use of visual cues (a mechanical alignment guide or the transverse acetabular ligament, TAL) can improve surgical accuracy when compared to a freehand approach. Use of the transverse acetabular ligament to control operative version combined with a mechanical alignment guide for controlling operative inclination was the optimum choice for reducing acetabular positioning errors in their study. If a mechanical alignment guide is used alone (for controlling both operative inclination and operative version), it can result in a high incidence of acetabular cups being placed unsafely (n=21/50) as illustrated by Hassan et al.¹⁷² A limitation of the study carried out by Grammatopoulos et al¹⁷¹ was that it used a surrogate pelvic model and the orthopaedic surgeons involved were aware of the fact that they were being tested for accuracy. Intra-operative factors such as a high body mass index (obesity) may further impede an orthopaedic surgeon's ability to achieve their desired target operative acetabular orientation.¹⁷³⁻¹⁷⁵ Despite the improvement in mean accuracy over the freehand approach, large ranges between the intended target operative orientation and that achieved persisted in the study carried

out by Grammatopoulos et al¹⁷¹ (operative inclination controlled by mechanical alignment guide: -21° to 4° ; operative version controlled by transverse acetabular ligament: -17° to 11°). These ranges exceed the width of the safe zone ($\pm 5^{\circ}$) proposed by Grammatopoulos et al⁴⁰ for reducing both the rate of dislocation and increasing functional outcomes.

Like Grammatopoulos et al,¹⁷¹ Meermans et al¹⁷⁶ illustrated improved acetabular orientations when using TAL to control operative version compared to the use of a mechanical alignment guide. Unlike the study by Grammatopoulos et al,¹⁷¹ the study by Meermans et al¹⁷⁶ was carried out within a clinical setting. TAL version is patient-specific²⁶ and may not conform to fixed radiographic safe zones. In spite of this, Meermans et al¹⁷⁶ observed that all of their cases involving TAL were within the Lewinnek safe zone. A limitation of the TAL approach is that it can only be used to control operative version. A freehand approach or a mechanical alignment guide are still required to control operative inclination and, as such, incur their surgical inaccuracies. A further possible pitfall of the TAL approach, is that the ligament may not be easily identifiable in all patients during surgery.¹⁷⁷⁻¹⁷⁸ Epstein et al¹⁷⁸ could only identify the TAL in 47% ($n=30/64$) of their cohort. They concluded that osteophytes impeded identification of the TAL. However, Archbold et al²⁶ has highlighted that TAL was identifiable in 99.7% ($n=997/1000$) of their cohort when soft tissue and or osteophytes were cleared. Without clearance, the findings of Archbold et al²⁶ confer with those of Epstein et al¹⁷⁸, with the ligament being visible in only 49% ($n=490/1000$) of their cohorts without additional clearance. Regardless, the use of the TAL for guiding operative version has been associated with a reduced risk of dislocation.²⁶

Computer aided orthopaedic surgery (CAOS) is used in less than 1% of orthopaedic surgeries within the UK.¹⁰ Widespread adoption of CAOS may be limited due to a lack of increased surgical benefit when balanced against the increased cost of CAOS. The cost of CAOS is subject to the need for specialised equipment,¹⁷⁹⁻¹⁸⁰ increased operating times,¹⁷⁹⁻¹⁸³ and a steeper learning curve.^{180,182} With respect to surgical benefit, studies to date have illustrated that no statistical differences for the mean angles of inclination and version achieved post-operatively were observed between CAOS and conventional techniques (mechanical alignment guide and freehand).¹⁸⁴⁻¹⁸⁷ However, one study by Lass et al¹⁸⁸ did observe significant differences between the mean angles of version achieved post-operatively when using CAOS and a freehand approach. Despite studies exhibiting no significant differences in the mean inclination and version achieved, many have indicated reduced variability of the acetabular cup orientation achieved when using CAOS.^{183-184,187,189-191} Several of these studies also found a higher incidence of acetabular cups being placed within their targeted safe zones when using CAOS.^{181, 184-185,187} Nevertheless, even with the use of CAOS, it is clear that a wide range of acetabular orientations have still been reported. These ranges still exceed the widths of proposed safe zones and CAOS does not eliminate the outliers that plague conventional techniques.

2.4 Pelvic Positioning

As discussed in Chapter 1, pelvic positioning can have an impact on the accuracy of acetabular component positioning intra-operatively. Additionally, post-operative pelvic positioning during the acquisition of routine anterior-posterior pelvic radiographs can impair the perceived position of radiographic acetabular component orientation achieved.

2.4.1 Intra-operative Positioning

During THR surgery, the majority of patients within the UK are operated on in the *lateral decubitus* position.¹⁰ Patients are held in the *lateral decubitus* position intra-operatively via the use of surgical supports. Traditionally, it was assumed that these supports maintained the patient's pelvis in a neutral position during surgery. Theoretically, pelvic neutrality in the lateral decubitus position is achieved when the pelvic sagittal plane is parallel to the theatre floor and the anterior pelvic plane (APP) is parallel to the long axis of the theatre table.¹⁹² Although the former is possible, the latter is unlikely because of the large natural variation in the relationship between the APP and the long axis of the patient.²⁸ Within the literature, there are a limited number of studies that have detailed the extent of pelvic mal-orientation during surgery.^{27,193-195} However, from these studies, it has been illustrated that the pelvis deviates from the assumed neutral position during THR.^{27,193-195} Initial mal-alignment, during patient positioning, and intra-operative forces can force the pelvis to deviate from neutrality.²⁷ Both of these factors can be influenced by the surgeons approach for patient positioning and by the choice of supports used for patient fixation during THR.

For external landmark approaches (freehand and mechanical alignment guide), if the pelvis has deviated from neutrality, then the angle the introducer makes with the theatre floor and table longitudinal axis is not the same as the angle the introducer makes with the pelvic sagittal plane and anterior pelvic plane (Figure 1.18). Subsequently, the cup will be placed at an unknown angle relative to the operative pelvis and radiographic variability in acetabular cup orientation will result post-operatively. The use of CAOS attempts to forgo the problems of conventional techniques by monitoring the intra-operative position of the pelvis at the time of acetabular impaction.²⁵ However, even CAOS is not immune to inaccurate placement.

For example, image-free CAOS is limited by the palpation process required to register the pelvis at the beginning of surgery; inaccurate palpation through soft tissue and surgical drapes can lead to pelvic registration errors and subsequently cup malalignment.¹⁹⁶

2.4.2 Post-operative Assessment of Acetabular Component Placement

Variability for measured acetabular cup orientation may also result from patient positioning during the acquisition of an anterior-posterior pelvic radiograph taken post-operatively. During the acquisition of an anterior-posterior pelvic radiograph, patients are generally arranged in a supine position (on their back), in contrast to the *lateral decubitus* positioning used during surgery. In the supine position, the degree of pelvic tilt (angle between the anterior pelvic plane and the coronal radiograph plane) is patient-specific.²⁸ The sum of pelvic tilt and the degree of anteversion at which the acetabular cup was implanted relative to the pelvis impacts the degree of anteversion and inclination (to a lesser degree) projected on the radiograph (Figure 2.20).¹⁹⁷

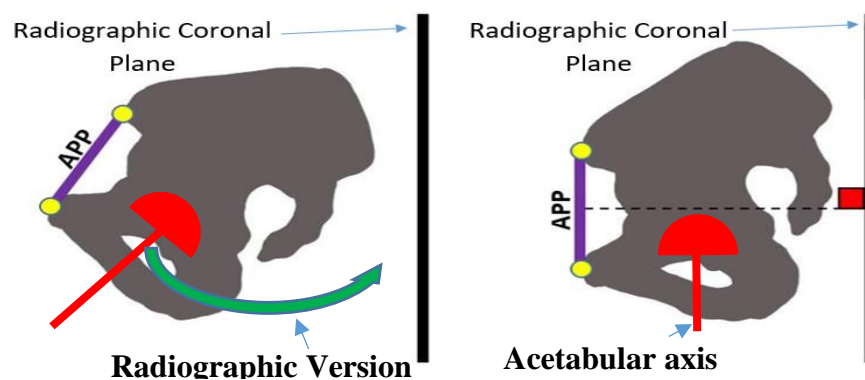


Figure 2.20 Pelvic positioning during radiography influences the location of the acetabular axis relative to the radiographic coronal plane and thus the degree of radiographic version.

Without correction for pelvic tilt, each set of measurements for radiographic inclination and version for each patient will be from a different reference frame and

therefore comparisons are compromised (particularly for anteversion). This will contribute to the observed variability in radiographic assessment of surgical outcomes. The use of CT scans instead of anterior-posterior pelvic radiographs can be used to establish a common reference frame of measurement.¹⁹⁸⁻²⁰² However, anterior-posterior radiographs are more widely adopted for THR due to their lesser expense and reduced radiation exposure.

Tannast et al²⁰³ used 2D measures of pelvic anatomical relationships from anterior-posterior pelvic radiographs to predict the degree of pelvic tilt. Of the relationships investigated, only the distance between the upper border of the pubic symphysis and the sacrococcygeal joint was found to have a moderate correlation with pelvic tilt (Figure 2.21). This relationship was gender dependant and was found to be stronger for men ($r=0.68$, $n=41$, $p<0.01$) than women ($r=0.63$, $n=63$, $p<0.01$).



Figure 2.21 2D measurement of the distance between the upper border of the pubic symphysis and the sacrococcygeal joint were found to have the strongest correlation with pelvic tilt.²⁰³

Multiple planar radiographic views have been previously used to assess the degree of pelvic tilt.²⁰⁴⁻²⁰⁵ The key limiting factor for this approach is that it exposes each patient to an increased level of radiation exposure. Additionally, it has been shown that the degree of pelvic tilt changes between the standing and supine position.^{68, 205} Therefore,

for the measure of pelvic tilt to be an applicable correction factor for acetabular orientation within the anterior-posterior radiographic reference frame, the patient position in which the additional view was taken must be the same as the supine patient position in which the anterior-posterior radiograph was taken.

Statistical shape models of the pelvis have been introduced as a method for determining the spatial orientation of the pelvis within the anterior-posterior radiographic reference frame.²⁰⁶⁻²⁰⁷ Statistical shape models are deformable models that represent the mean shape of an object and the allowable variance in shape within a family of similar objects.²⁰⁸ Current approaches employing statistical shape models for reconstructing pelvic orientation from a single anterior-posterior radiograph rely on approaches in which landmarks from the pelvic model are iteratively fitted to corresponding landmarks selected on the anterior-posterior pelvic radiograph. These approaches rely on the use of the anterior superior iliac spines. However, low anterior-posterior radiographs can cut off the top of the pelvis and the anterior superior iliac spines may not be visible within the view of the radiograph.

2.5 Optimisation

Often, it is required to find the optimum solution or a set of design variables that minimise a fitness function. For example, Lewinnek et al¹¹⁵, aimed to determine the 2D radiographic acetabular orientations (the design variables) that would minimise the risk of dislocation. In this instance, the fitness function was a count of the number of dislocations at each acetabular radiographic orientation. At times, linear solutions can be applied to minimise fitness functions. For example, least squares fitting of an ellipse.

If linear algebraic manipulation cannot be applied to find the solution of a mathematical problem, an alternative approach is required. One approach is to use an exhaustive search algorithm. With an exhaustive search algorithm, the fitness function is evaluated for every possible combination of design variable. The search space, the range of design variables investigated, may be constrained to reduce the number of trials in such cases. For example, if an orthopaedic surgeon wanted to determine the radiographic acetabular orientations that minimised ceramic squeaking, they may limit the search space to those acetabular orientations defined within Lewinnek's safe zone¹¹⁵ for minimising the risk of dislocation. Although constraining the search space of an exhaustive search algorithm improves its efficiency, exhaustive search is still the most computationally expensive approach for evaluating a non-linear fitness function.

Optimisation is a mathematical technique for finding an optimal solution to an objective function. When discussing optimisation techniques, there are two main categories: (1) local and (2) global optimisation algorithms. An example of a local optimisation algorithm is the Hill Climbing algorithm²⁰⁹, which is gradient-based. To use gradient based algorithms, the fitness function must be modelled in such a manner that a first order derivative (or the gradient) of the function can be obtained at each step.

Initialisation of gradient-based searches involves selecting a series of design variables from which to commence the search. Following initialisation, the position or value of the design variable is iteratively updated by moving it in the direction of the gradient by a step length proportional to its gradient (Figure 2.22). When the magnitude of the gradient diminishes, i.e. minimal changes in position are observed - the solver has found the optimum solution to the problem.

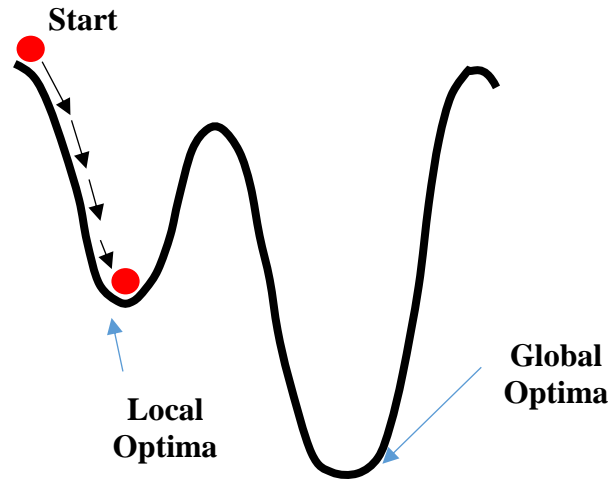


Figure 2.22 Gradient based solver stuck in local optima.

A limitation of gradient-based approaches is that they are not suited to functions in which there are multiple local optima within the search space. In the presence of multiple local optima, the solution provided by gradient-based searches is heavily influenced by the initial position or initial design variables used to initialise the solver (Figure 2.22). Consequently, they may provide sub-optimal solutions.

Global optimisation seeks to find global optima even in the presence of numerable local optima. To avoid the problem of selecting an erroneous initial starting position or design variable, global optimisation employs a population of multiple starting positions. As such, even if some of the search particles fall into local optima, others remain to find the global solution. Examples of global optimisation algorithms include particle swarm optimisation (PSO)²¹⁰ and genetic algorithms (GA)²¹¹.

Genetic algorithms²¹¹ are based on the process of natural selection. Members of a population are more likely to survive and reproduce if they have characteristics that make them suited to their environment. These characteristics are passed onto their offspring in the next generation. Within GA, the initial population or the first

generation of search particles are randomly generated. Subsequent generations are created from the members of this generation. For each generation, the fitness of every search particle is obtained. Parents of the generation are then chosen based on their fitness values (survival of the fittest). Children, or the next generation of search particles, are produced by either applying a mutation to a single parent (a random change to the genetic chromosome or design variables of one parent e.g. scrambling) or by combining parents (cross-over, a combination of two parent's genetic chromosomes or design variables e.g. an average). When the children are formed, they replace the current generation of search particles and the process begins again. The solver terminates when a member (combination of design variables) has a fitness value less than a pre-defined threshold.

Particle swarm optimisation²¹⁰ is based on the concept of swarm intelligence. A swarm consists of many individuals. The overall behaviour or movement of the swarm is influenced by communication between members of the swarm. As with GAs, the initial phase of a PSO is to randomly generate an initial population of search particles. Unlike GAs, the members of the search population remain present through each iteration of the solver, i.e. no mutations or cross-overs. In each iteration, the search particles move through the search space. The velocity of each search particle is updated via knowledge of their own personal best fitness and by the knowledge of the overall best fitness of the swarm. This velocity vector is used to update the position of the particles for the next iteration. PSO has been shown to provide equivalent results to GAs.²¹²⁻²¹⁴ In these instances, the use of a PSO is often faster than a GA for determining the global solution to a problem as the structure of a PSO algorithm is less complicated (no mutations and cross-overs).

2.6 Aims and Objectives

Although THR is a successful operation with current survivorship exceeding 90% at 10 years,³⁴ negative outcomes such as dislocation and aseptic loosening persist.¹ As discussed, both the choice of implant (bearing material and size) and the orientation of the implant impact the longevity of the joint. To date, a wide range of acetabular component orientations are observed on post-operative radiographs despite typically using fixed operative target angles.^{29-30,40-41} Both intra-operative and post-operative pelvic orientation contribute to this variance. With the upcoming THR burden, an opportunity exists for creating cost effective tools that can be used to reduce the variability between operative and radiographic acetabular orientation.

In order to ultimately decrease the risk of negative outcomes, this thesis aimed to bridge the gap in understanding between intra-operative control and post-operative measures of acetabular orientation. Given the continuing demand for conventional 2D radiography for post-operative assessment, this work sought to answer the question of how pelvic orientation affects acetabular cup orientation in current practice and whether it can be accounted for without the use of expensive tools or additional radiation exposure. To achieve the overall aim and answer the above research question, a number of objectives were identified:

1. Statistically analyse the current state of the art in surgical hip props, patient positioning methods and surgical techniques in order to identify mechanisms in modal current practice that influence cup orientation as a result of pelvic positioning (Appendix A).
2. Establish, theoretically, the impact of intra-operative pelvic movement on acetabular orientation with relation to current practice. This will enable primary

modes of intra-operative pelvic mal-rotation that contribute to the variance observed between operative and radiographic measures of acetabular orientation to be identified.

3. Having identified the key modes of pelvic mal-rotation, develop, trial, and evaluate a technique for aiding the surgeon in controlling pelvic position and orientating the acetabular component intra-operatively with respect to these primary modes of intra-operative pelvic mal-rotation.
4. Improve post-operative assessment of acetabular component placement without the use of a CT scan or additional radiographic views. Identify the impact of magnification errors and radiographic pelvic positioning on the observed differences between the operative and radiographic measures of acetabular orientation and estimate true orientation with respect to the pelvic reference frame.
5. Combine the theoretical understanding of pelvic mal-rotation (Objective 2) with the post-operative assessment tool (Objective 4) to estimate intra-operative pelvic orientations without the use of CAOS. This tool can then be applied to a clinical cohort to identify primary modes of intra-operative pelvic mal-rotation that contribute most to the variance observed between operative and radiographic measures of acetabular orientation in clinical practice.

The first three objectives relate primarily to intra-operative control of acetabular component placement. Objective 1 will identify current modal surgical practices with respect to patient positioning and acetabular component placement. To reduce disruption to current surgical practice and undue cost, techniques developed within this thesis will build upon modal practices identified during Objective 1. With respect to acetabular component orientation, Objective 2 will theoretically highlight the key

modes of pelvic mal-rotation that will result in a deviation between what an orthopaedic surgeon observes in surgery (relative to external theatre landmarks e.g. floor), and what is obtained relative to the bony pelvis due to use of current navigation approaches. This information will be used to develop cost effective strategies to prevent such pelvic mal-rotations (Objective 3) in order to improve intra-operative control of the acetabular component.

Objective 4 relates to the impact of patient positioning during radiography on the accuracy of post-operative assessment of acetabular component orientation. It seeks to improve upon estimates for true acetabular component orientation and thus bridge the gap between intra-operative and post-operative measures for acetabular orientation. Given the continuing demand for conventional 2D radiography, it seeks to do so without the use of CT scans or additional radiation exposure. Objective 5 aims to incorporate the findings of Objectives 2 and 4 alongside real clinical data to identify the likely pelvic mal-rotations that contribute most to deviation from target orientations in practice.

Successfully achieving the above objectives can significantly enhance understanding of the link between patient positioning, operative placement and post-operative acetabular component assessment. Additionally, it can also help to ultimately decrease risk of negative outcomes by applying such improved understanding to propose practical steps that can be taken to control acetabular component placement. For example, findings from successfully completing Objectives 2 and 5 can be used to develop/improve patient-positioning controls in order to minimise pelvic mal-rotation during surgery. Similarly, identifying the frequency of the key pelvic mal-rotations identified by Objective 2 using the tool to be developed for Objective 5 can help

determine target intra-operative acetabular orientations that best counteract the impact of intra-operative pelvic orientation with respect to current practice. As sufficient clinical outcome studies with detailed intra-operative and radiographic data accrue, the tools proposed here can better assess the relation between target and achieved acetabular component orientations and their correlation with specific clinical outcomes (e.g. dislocation). Ultimately, this should improve understanding of target orientations that reduce the risk of negative outcomes while simultaneously contributing to better intra-operative control so that such targets can be achieved.



THREE

Theoretical impact of pelvic positioning on operative acetabular cup orientation

Overview: The aim of this chapter was to theoretically investigate the relationship between current surgical practice, pelvic orientation and acetabular component mal-rotation (**Objective 2**). Two current surgical approaches were modelled: a mechanical alignment guide (MAG) and a transverse acetabular ligament (TAL) approach. Errors in acetabular component orientation were observed about all three axes of pelvic rotation for the MAG approach while errors were associated with two axes of pelvic rotation for the TAL approach. Use of the TAL approach theoretically eliminates errors in operative acetabular component version due to pelvic flexion / extension. However, affordable techniques are still needed to correct for pelvic adduction / abduction and internal / external rotation when using the TAL approach. Pelvic adduction / abduction is of particular theoretical concern due to its near linear relationship with errors in operative acetabular inclination.

3.1 Introduction

Murray defined operative acetabular orientation with respect to the patient's sagittal plane in terms of inclination and version (Chapter 1.7, Figure 1.12).¹⁶ During THR surgery, the sagittal pelvic plane is obscured. As such, surgical approaches for orientating the acetabular component may employ alternative landmarks. When using a mechanical alignment guide (MAG) in *lateral decubitus*, operative inclination (Figure 3.1) is referenced off the theatre floor (as a surrogate for the pelvic sagittal plane) and operative version (Figure 3.2) is taken as the angle between the longitudinal axis of the theatre table (or patient longitudinal axis) and the acetabular axis as projected onto the theatre floor.

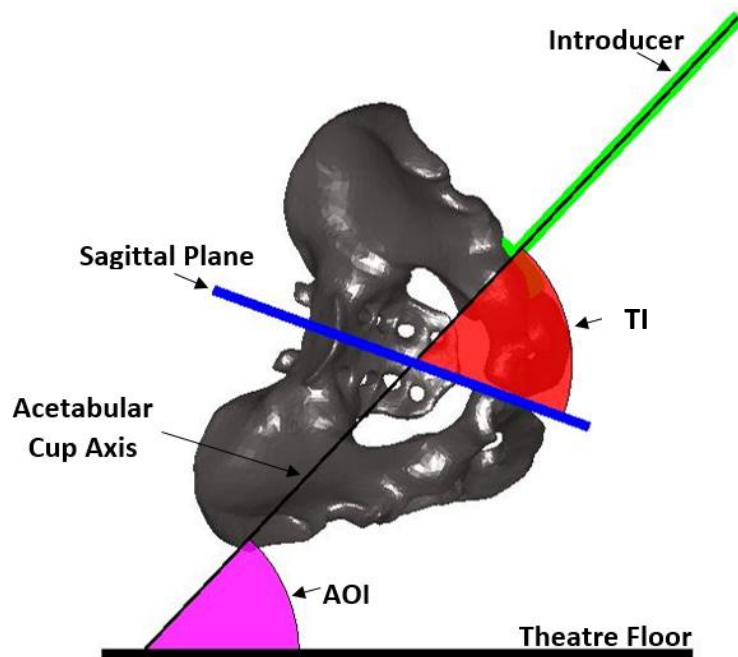


Figure 3.1 Apparent operative inclination (AOI) and true inclination (TI): TI is the angle between the acetabular cup axis and the pelvic sagittal plane. This is equivalent to Murray's definition of operative inclination. AOI is the angle between the acetabular cup axis and the theatre floor.

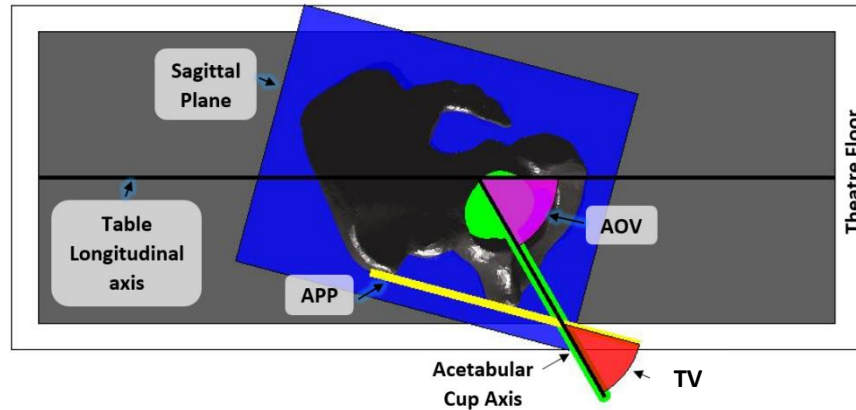


Figure 3.2 Apparent operative version (AOV) and true version (TV): AOV is the angle between the acetabular cup axis and theatre table longitudinal axis as projected onto the theatre floor; TV is the angle between the acetabular cup axis and anterior pelvic plane (APP) as projected onto the pelvic sagittal plane. If the pelvic APP is parallel to the longitudinal axis, TV is equivalent to Murray's definition of operative version.

Use of the theatre floor and the theatre table's longitudinal axis as landmarks rely on the assumption that the pelvis is in a neutral position intra-operatively. Pelvic neutrality in *lateral decubitus* is achieved intra-operatively when the pelvic sagittal plane is parallel to the theatre floor and the anterior pelvic plane (APP) is parallel to the patient's longitudinal axis or coronal plane. In reality, the APP is rarely parallel to the patient's coronal plane. Angles referenced from external theatre landmarks (e.g. theatre floor and table) will, therefore, become apparent angles for operative inclination and version. Discrepancies between true (relative to pelvic sagittal plane and anterior pelvic plane) and apparent (relative to theatre floor and table) operative acetabular component orientation will contribute to inconsistencies between the orthopaedic surgeon's expectations and the reality of post-operative X-ray measurements when using a MAG approach (Figure 3.1, Figure 3.2).

The transverse acetabular ligament (TAL) has been used to determine patient-specific operative version (TV) relative to the anterior pelvic plane.²⁶ Although independent of patient position, it does not provide a solution for operative inclination. To control operative inclination, TAL is often used with a MAG or freehand approach. For the reasons discussed above, pelvic mal-positioning and patient-specific TAL version will contribute to radiographic variability when using this approach.

The aim of this chapter was to theoretically investigate the relationship between current surgical practice, pelvic orientation, and acetabular component mal-rotation (Objective 2). Two different surgical techniques were simulated using a pelvic model for a given target acetabular orientation. The first simulated surgical technique used the surgical theatre table longitudinal axis to control operative version, which is equivalent to using the “version guide” on a MAG. The second used the TAL approach. For operative inclination, both techniques used the theatre floor. These two techniques are the most commonly adopted in current THR practice in the UK (Appendix A, Objective 1). Having developed the theoretical models, the purpose of this study was to identify the modes of intra-operative pelvic mal-rotation which are most likely to contribute to the observed variability between true and apparent operative acetabular orientation (Objective 2).

3.2 Method

A pelvic model was initially orientated to match the idealised *neutral* pelvic orientation for a patient undergoing THR surgery of a left hip in *lateral decubitus*. The pelvic model was then mal-rotated and a simulated acetabular cup inserted. The orientation of the acetabular component relative to the external theatre floor and table longitudinal axis with the pelvis mal-rotated provided measures of apparent operative acetabular

component orientation. With the simulated acetabular component in place, the pelvic mal-rotation was reversed and measures of true operative acetabular orientation were gained (relative to the APP and sagittal pelvic plane). Both the impact of single-axis pelvic rotations and combined pelvic rotations were investigated.

3.2.1 Theory: Frames of Reference, Orientation Vectors, and Rotations

A Sawbones[®] pelvis (Sawbones Europe AB, Sweden) was scanned (Hexagon Global Status CMM 092008, Renishaw PH10M Nikon LC50 Laser with Nikon Focus scan software, Rapidform, PTC Creo, USA) and imported into MATLAB (2015b, The MathWorks Inc., USA) as a surface mesh. The pelvis was aligned within MATLAB such that the centre of its APP was coincident with the origin of a right handed Cartesian coordinate reference frame (Figure 3.3).

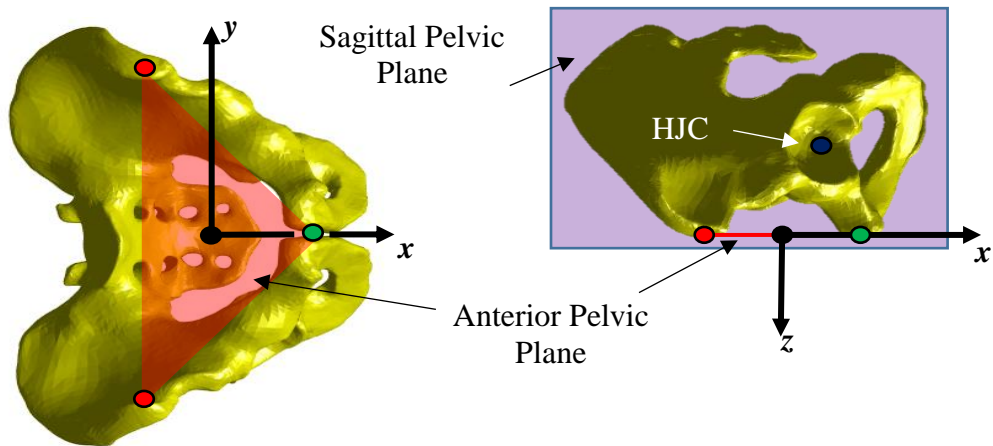


Figure 3.3 Alignment of pelvic model within MATLAB. The pelvic model was arranged so that its anterior pelvic plane was parallel to the x-y plane (theatre table longitudinal axis) and its sagittal pelvic plane parallel to the x-z plane (theatre floor). The pelvic model was simplified by selecting a point depicting the hip joint centre-of-rotation (HJC) relative to the neutral pelvis.

To ensure neutral pelvic positioning, the APP of the pelvic model was positioned parallel to the x - y plane (theatre table longitudinal axis) whilst the sagittal pelvic plane was positioned to be parallel to the x - z plane (theatre floor). In this position, the location of the left hip joint's centre-of-rotation was selected. Use of the hip joint centre-of-rotation and APP landmarks can be used to create a simplified point model of the pelvis.

Rotation of the pelvis about its longitudinal axis (Cartesian x -axis) was regarded as internal (+) / external (-) rotation. Rotation of the pelvis about its anterior-posterior axis (Cartesian z -axis) was regarded as abduction (+) / adduction (-). Rotation of the pelvis about its transverse axis (Cartesian y -axis) was termed anterior (+) / and posterior (-) pelvic tilt (Figure 3.4).

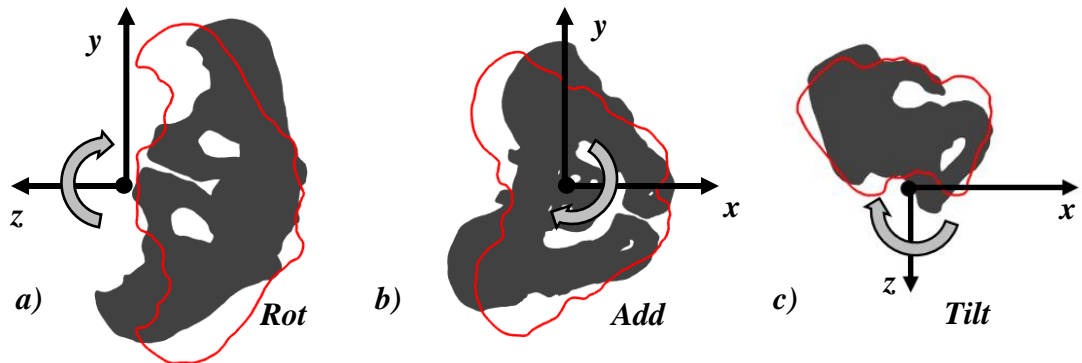


Figure 3.4 *Negative elemental pelvic rotations for a left operative hip (neutral pelvic outline depicted in red): a) external rotation b) adduction c) posterior tilt.*

Mal-orientation of the neutral pelvic model and, thus, its hip joint centre-of-rotation within the operative reference frame about its three axes can be achieved via a sequence of elemental rotations (Equations 1, 2, and 3).

$$R_x(rot) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(rot) & -\sin(rot) \\ 0 & \sin(rot) & \cos(rot) \end{bmatrix} \quad (1)$$

$$R_z(add) = \begin{bmatrix} \cos(add) & -\sin(add) & 0 \\ \sin(add) & \cos(add) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$R_y(tilt) = \begin{bmatrix} \cos(tilt) & 0 & \sin(tilt) \\ 0 & 1 & 0 \\ -\sin(tilt) & 0 & \cos(tilt) \end{bmatrix} \quad (3)$$

Where:

rot angle of internal/external rotation

tilt angle of anterior/posterior tilt

add angle of abduction/adduction

For this investigation the mal-rotated operative position of the hip joint centre-of-rotation (\hat{c}_R) relative to its neutral position (\hat{c}_N) was calculated using Equation 4. Although the order in which the rotations are applied can impact the resultant position of the pelvis, by including all possible combinations within acceptable limits, the majority of allowable pelvic orientations should be incorporated.

$$\hat{c}_R = R_z(add)R_x(rot)R_y(tilt)\hat{c}_N \quad (4)$$

3.2.1.1 MAG Approach

In practice the acetabular cup would be inserted relative to the rotated pelvis's hip joint centre-of-rotation (\hat{c}_R) intra-operatively. For the MAG approach, this is achieved by orientating the introducer relative to the theatre floor and table longitudinal axis. Initially, the introducer axis was treated as a unit vector collinear with the operative x-axis (\hat{e}_1). To achieve the apparent operative orientation of the introducer axis for the MAG method (\hat{i}_{AM}), Equation 5 was used. In practice, the introducer axis is a vector that would be collinear with the handle of the introducer and perpendicular to the face of the acetabular cup being inserted.

$$\hat{\mathbf{i}}_{\text{AM}} = (\mathbf{R}_y(-AOV)\mathbf{R}_z(AOI)\hat{\mathbf{e}}_1) + \hat{\mathbf{c}}_{\text{R}} \quad (5)$$

3.2.1.2 TAL Approach

In current practice, an orthopaedic surgeon employs the TAL approach by rotating the introducer about the hip joint's centre of rotation whilst ensuring that the introducer remains at a right angle to the TAL when projected onto the sagittal plane. This maintains the true version relative to the APP or bony pelvis. Mathematically, this can be achieved by introducing an equivalent TAL axis ($\hat{\mathbf{t}}_{\text{N}}$, about which the introducer will rotate) that is coincident with the hip joints centre of rotation and parallel to the native TAL axis when projected onto the sagittal plane (Figure 3.5). Neutral operative coordinates (i.e. when the pelvis is in a neutral orientation) of the equivalent TAL axis ($\hat{\mathbf{t}}_{\text{N}}$) within the operative reference frame can be obtained from Equation 6 where $\hat{\mathbf{e}}_3$ represents a unit vector coincident with the operative z -axis.

$$\hat{\mathbf{t}}_{\text{N}} = (\mathbf{R}_{\text{y}}(-TV)\hat{\mathbf{e}}_3) + \hat{\mathbf{c}}_{\text{N}} \quad (6)$$

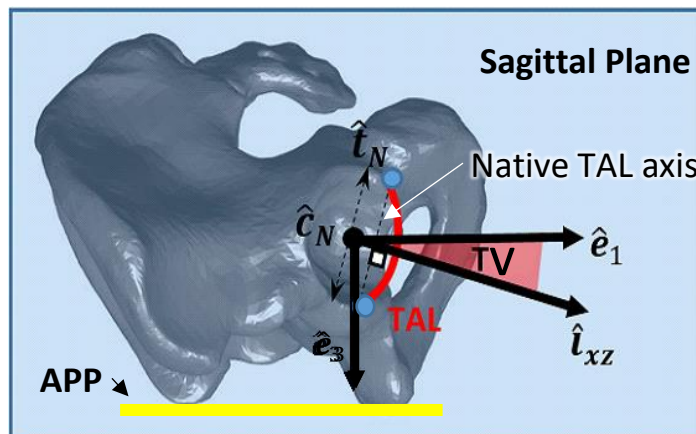


Figure 3.5 Orientating introducer relative to neutral TAL version. The equivalent TAL axis ($\hat{\mathbf{t}}_N$) was treated as a unit vector, parallel to TAL (i.e. a line intersecting TAL, highlighted in blue, and perpendicular to the introducer axis), whose centre was

coincident with the hip joint centre-of-rotation ($\hat{\mathbf{c}}_N$), about which the introducer ($\hat{\mathbf{i}}$) rotated in order to achieve the desired operative inclination.

Similar to the method used to obtain the coordinates of $\hat{\mathbf{c}}_R$ (Equation 4), the operative coordinates of the equivalent TAL axis relative to the rotated pelvis ($\hat{\mathbf{t}}_R$) can be obtained by substituting $\hat{\mathbf{c}}_N$ with $\hat{\mathbf{t}}_N$. The apparent operative position of the introducer axis for the TAL method can then be found by rotating the introducer axis about the equivalent TAL axis ($\hat{\mathbf{t}}_R$). A custom solver (Equation 10, Figure 3.6, Figure 3.7) was developed to determine the angle (α) that the apparent introducer axis for the TAL method ($\hat{\mathbf{i}}_{AT}$) would have to rotate about the $\hat{\mathbf{t}}_R$ axis to provide the target AOI where $\hat{\mathbf{i}}_{ATxz}$ represents the TAL introducer axis projected onto the theatre floor (x - z plane). For further details pertaining to the solver, see Appendix B.

$$f(\alpha) = AOI - \cos^{-1}(\hat{\mathbf{i}}_{AT} \cdot \hat{\mathbf{i}}_{ATxz}) \quad (10)$$

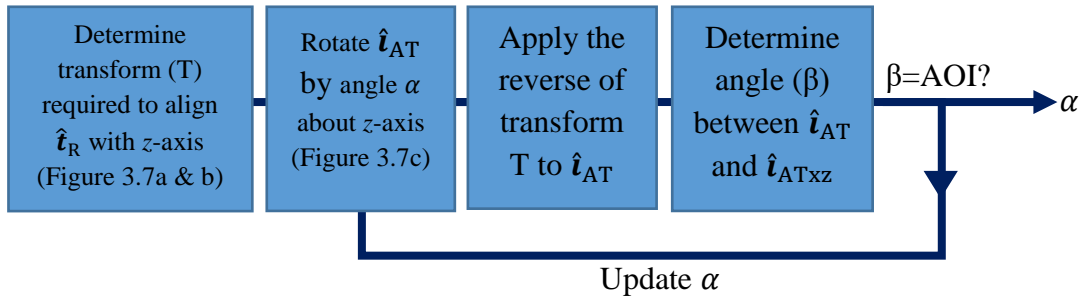


Figure 3.6 Overview of solver used to determine the angle α about the TAL axis ($\hat{\mathbf{t}}_R$) that the introducer ($\hat{\mathbf{i}}_{AT}$) must rotate to achieve the target AOI

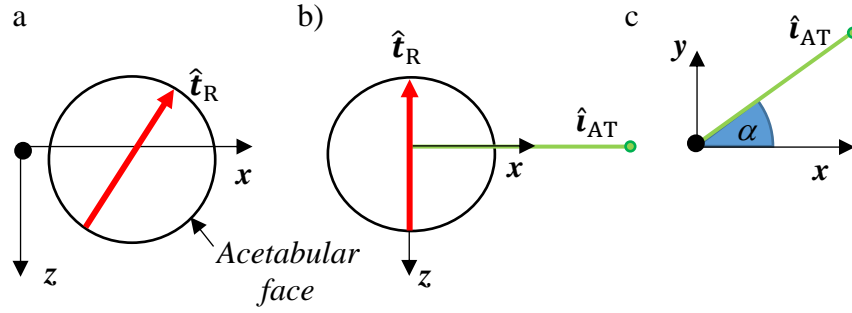


Figure 3.7 Reference frame used to determine the angle α about the TAL axis (\hat{t}_R) that the introducer (\hat{i}_{AT}) must rotate to achieve the target AOI

3.2.1.3 Apparent operative and true orientation of the introducer axis

Apparent operative inclination (AOI) was defined as the angle between the acetabular component axis and the surgical theatre floor. **Apparent operative version** (AOV) was defined as the angle between the acetabular component axis and the surgical theatre table longitudinal axis as projected onto the surgical theatre floor (\hat{i}_{Axz}). Measures of apparent operative inclination and version for the apparent introducer axis (\hat{i}_A) relative to the theatre floor (x - z plane) and table longitudinal axis (x -axis, \hat{e}_1) can be obtained using Equations 7 and 8.

$$AOI = \cos^{-1}(\hat{i}_A \cdot \hat{i}_{Axz}) \quad (7)$$

$$AOV = \cos^{-1}(\hat{e}_1 \cdot \hat{i}_{Axz}) \quad (8)$$

Having positioned the apparent introducer axis (\hat{i}_A) relative to the rotated pelvis, the true introducer axis (\hat{i}_T) relative to the pelvic sagittal plane and APP can be determined by reversing the rotations applied in Equation 4. **True inclination** (TI) was defined as the angle between the acetabular component axis and its projection onto the pelvic sagittal plane (\hat{i}_{Txz}). **True version** (TV) was the angle between the acetabular

component axis and the anterior pelvic plane (\hat{e}_1) as projected onto the pelvic sagittal plane. Measures for TI and TV can be determined from Equations 9 and 10.

$$TI = \cos^{-1}(\hat{i}_T \cdot \hat{i}_{Txz}) \quad (9)$$

$$TV = \cos^{-1}(\hat{e}_1 \cdot \hat{i}_{Txz}) \quad (10)$$

3.2.2 Analysis

In all cases a target AOI of 35° was used. For the MAG method, a target AOV of 20° was used. To enable comparability, a target TV of 20° was used for the TAL method. In practice, this would reflect the native version of the TAL. The impact of both single-axis and combined rotations on true acetabular orientation was investigated. For single axis rotations, a theoretical range (-30° to 30° in steps of 1°) was applied to each axis of rotation independently. This resulted in the creation of three datasets with measures of TI and TV due to pelvic malrotation (one for each of the pelvic axes). For combined rotations, combinations about each of the three pelvic axes were applied simultaneously. All possible combinations within the desired range (-30° to 30° in steps of 1°) for each axis were considered. This resulted in the creation of a single dataset containing measures of TI and TV due to combined pelvic malrotations. Larger ranges were used than those reported²⁷ to account for the variability between practices.

With respect to single-axis rotations, regression analysis (linear and quadratic polynomial) was used to determine the impact of single-axis pelvic mal-rotations on true operative acetabular orientation. For combined rotations, multiple linear regression was applied. All analysis was carried out using SPSS (v22, IBM, USA) and MATLAB.

3.3 Results

3.3.1 Single-axis Rotations

For both methods, within the theoretical range investigated, regression analysis found that pelvic adduction / abduction showed the strongest linear relationship with changes in TI (Figure 3.8, Table 3.1). Although a non-linear relationship is evident with respect to the impact of external / internal rotation on TI for both approaches, due to the shallowness of the curves, linear regression was also suited to the MAG ($r^2 = 0.93$) and TAL approaches ($r^2 = 0.94$). As the motion of posterior / anterior tilt maintains the pelvic sagittal plane parallel to the theatre floor, pelvic posterior / anterior tilt was found to have no impact on TI.

Conversely, for single-axis pelvic rotations relative to the MAG method pelvic posterior / anterior tilt was found to have the strongest linear relationship with TV (Table 3.2, Figure 3.9). The angle of pelvic tilt is coplanar with the angle of TV so any changes in pelvic tilt will result in a direct change in TV for the MAG method. Unlike TI, the TAL approach maintains the TV relative to the APP. As such, when using the TAL approach, there are no deviations in the TV observed. As before, although non-linear relationships are apparent between TV and two of the single-axis pelvic rotations when using a MAG approach, regression analysis revealed strong linear correlations (Table 3.2).

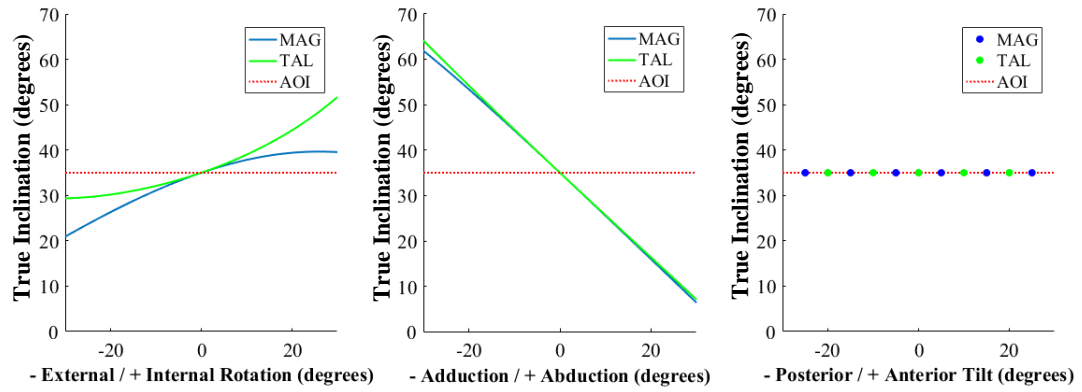


Figure 3.8 *Impact of single-axis rotations for MAG and TAL approaches on TI (relative to the pelvic system) relative to target AOI (horizontal red line; relative to the operative system). Pelvic adduction / abduction displays the strongest linear relationship with TI.*

Table 3.1 *Investigating the impact of single elemental pelvic rotations on TI via regression analysis*

			<i>Coefficients</i>			
	<i>Approach</i>	<i>Regression</i>	<i>Intercept</i>	θ	θ^2	r^2
<i>Ext Int</i>	MAG	Linear	33.38	0.32	0	0.93
		Polynomial	35	0.32	0.0053	1
	TAL	Linear	36.8	0.36	0	0.94
		Polynomial	35	0.36	0.0061	1
<i>Abd Add</i>	MAG	Linear	34.7	- 0.93	0	1
	TAL	Linear	35.2	- 0.95	0	1
<i>Post Ant</i>	MAG	Linear	35	0	0	1
	TAL	Linear	35	0	0	1

Table 3.2 Investigating the impact of single-axis pelvic rotations on true version via regression analysis

			<i>Coefficients</i>			
	<i>Approach</i>	<i>Regression</i>	<i>Intercept</i>	θ	θ^2	r^2
<i>Ext Int</i>	MAG	Linear	18.5	- 0.64	0	0.99
		Poly	19.9	- 0.64	-0.0049	1
	TAL	linear	20	0	0	1
<i>Add Abd</i>	MAG	linear	21.9	- 0.29	0	0.87
		Poly	19.9	- 0.29	0.0068	0.99
	TAL	linear	20	0	0	1
<i>Post Ant</i>	MAG	linear	20	1	0	1
	TAL	linear	20	0	0	1

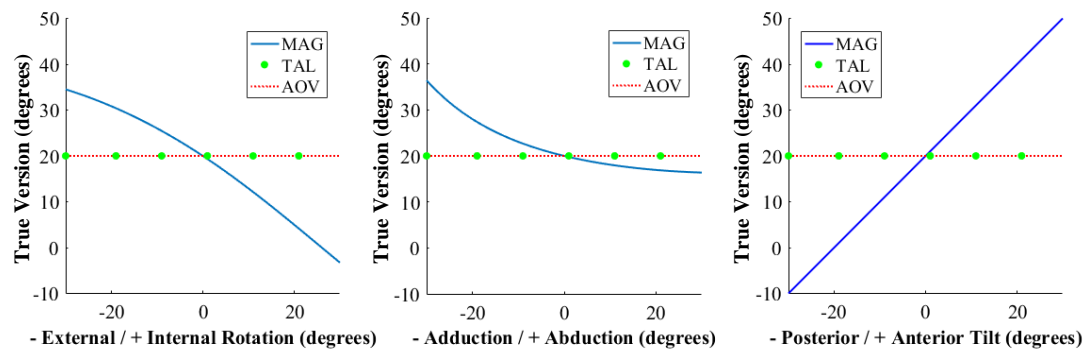


Figure 3.9 Impact of single-axis rotations on true version. Pelvic posterior / anterior tilt displays the strongest linear relationship with true version for the MAG approach. When using the TAL approach, TV was unaffected by changes in posterior / anterior pelvic tilt.

Of note, although no variability was observed in TV when using the TAL approach, substantial variability in the AOV was observed (Figure 3.10). This variability in AOV may negatively impact a surgeon's perception of native TAL version during surgery.

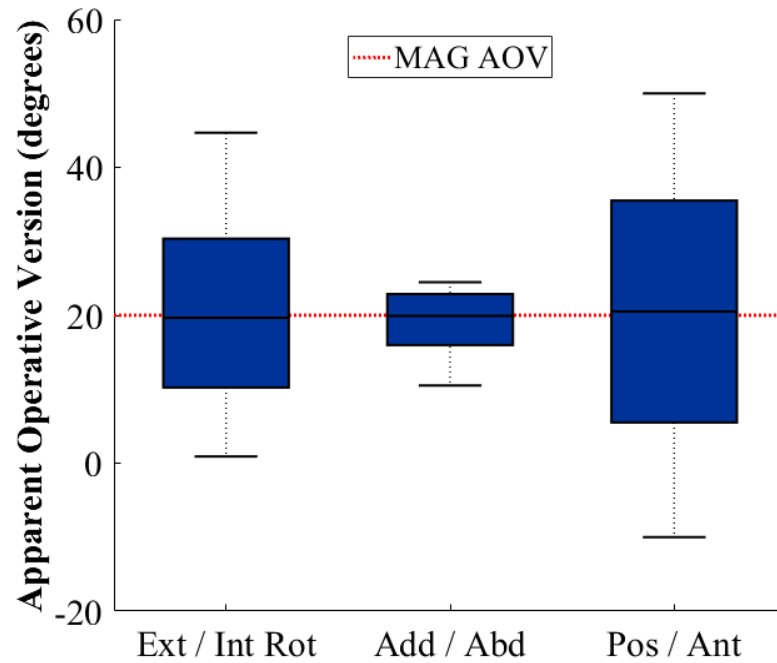


Figure 3.10 *The TAL method shows greater variability with respect to apparent operative version*

3.3.2 Combined Rotations

In practice, pelvic mal-rotations are unlikely to occur singularly. Thus, combined rotations were investigated for every possible combination within the theoretical range. With respect to combined pelvic rotations, the key observation was that the TAL approach theoretically eliminates errors for TV (Figure 3.11b). However, as the TAL approach ($\bar{x} = 37.3^\circ \pm 19.3^\circ$, -14.5° to 86.5°) relies on the theatre floor for achieving AOI, it results in comparable errors to the MAG ($\bar{x} = 32.8^\circ \pm 17.9^\circ$, -9.02° to 76.4°) approach for TI.

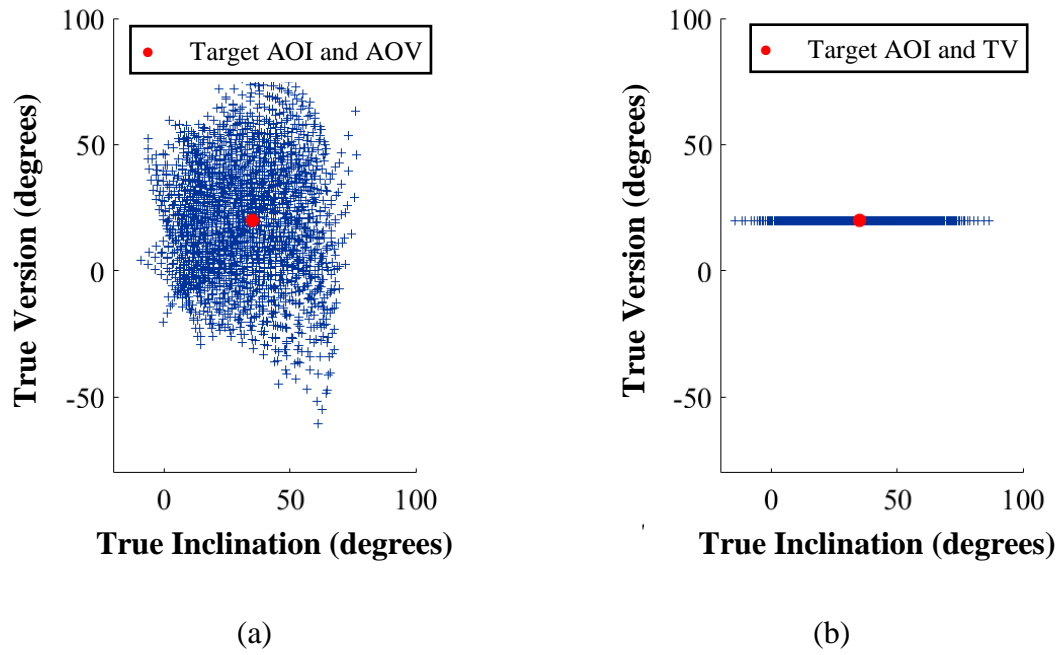


Figure 3.11 Impact of combined rotations on TI and TV when using the a) MAG and b) TAL approach. Use of the TAL method theoretically eliminates errors in true version

To understand the impact of combined pelvic rotations, multiple linear regression models were fit to TI ($r^2=0.942$, Table 3.3) and TV ($r^2=0.919$, Table 3.4) for the MAG approach and to TI for the TAL approach ($r^2=0.92$, Table 3.5). As the TAL approach exhibits no change in TV, multiple linear regression was applied to its TI only. For both approaches investigated, both pelvic external / internal rotation and pelvic adduction / abduction significantly contributed to the variance observed in TI. For the MAG approach, all pelvic orientations contributed to the observed variance in TV. For both the MAG ($\beta = -0.91$) and TAL ($\beta = -0.91$) approach, as with single-axis pelvic rotations, pelvic adduction / abduction exhibited the strongest linear relationship with TI. Similarly, for the MAG approach alone, posterior / anterior tilt ($\beta = 0.79$) illustrated the strongest relationship with TV.

Table 3.3 Investigating the impact of combined pelvic rotations on TI via multiple regression analysis for the MAG approach

<i>Model</i>	<i>Unstandardised Coefficients</i>		<i>Standardised Coefficients</i>	<i>T</i>	<i>p</i>
	<i>B</i>	<i>Std. Error</i>	<i>Beta</i>		
<i>(Constant)</i>	32.772	0.093		354.228	0.000
<i>Rot</i>	0.325	0.005	0.339	65.699	0.000
<i>Add</i>	− 0.871	0.005	− 0.909	− 176.083	0.000
<i>Tilt</i>	− 0.004	0.005	− 0.004	− 0.718	0.473

Table 3.4 Investigating the impact of combined pelvic rotations on TV via multiple regression analysis for the MAG approach

<i>Model</i>	<i>Unstandardised Coefficients</i>		<i>Standardised Coefficients</i>	<i>T</i>	<i>P</i>
	<i>B</i>	<i>Std. Error</i>	<i>Beta</i>		
<i>(Constant)</i>	19.670	0.147		133.846	.000
<i>Rot</i>	− 0.667	0.008	−0.517	−84.876	.000
<i>Add</i>	− 0.200	0.008	−0.155	−25.458	.000
<i>Tilt</i>	1.021	0.008	0.792	129.950	.000

Table 3.5 Investigating the impact of combined pelvic rotations on TI via multiple regression analysis for the TAL approach

<i>Model</i>	<i>Unstandardised Coefficients</i>		<i>Standardised Coefficients</i>	<i>T</i>	<i>P</i>
	<i>B</i>	<i>Std. Error</i>	<i>Beta</i>		
<i>(Constant)</i>	37.265	0.117		318.875	.000
<i>Rot</i>	0.328	0.006	−0.318	52.551	.000
<i>Add</i>	−0.935	0.006	−0.905	−149.672	.000
<i>Tilt</i>	0.005	0.006	0.005	0.860	.390

3.4 Discussion

The aim of this chapter was to theoretically investigate the relationship between current surgical practice, pelvic orientation, and acetabular component mal-rotation (Objective 2). For both surgical approaches investigated and TI variance, pelvic adduction / abduction (strongest) and external / internal rotation were found to be significant predictors. Whilst TV remained independent of pelvic orientation for the TAL approach, all modes of pelvic orientation were found to be significant predictors for TV variance for the MAG approach with pelvic posterior / anterior tilt being the strongest predictor.

From this study, it is clearly observed that an appropriate choice of surgical approach can reduce the resulting variance in true acetabular orientation. In this instance, use of the TAL method demonstrated better control of version compared with the MAG approach: the TAL method theoretically eliminated errors in TV ($TV_{\text{Range}} = 0.0^\circ$) when compared to the MAG method ($TV_{\text{Range}} = 146^\circ$). However, for TI, the TAL method ($TI_{\text{Range}} = 101^\circ$, $\bar{x} = 37.3^\circ \pm 19.3^\circ$) and the MAG method ($TI_{\text{Range}} = 85.4^\circ$, $\bar{x} = 32.8^\circ \pm 17.9^\circ$) both exhibited a large variation. The TAL method uses a fixed internal patient-specific landmark for controlling operative version, which can counteract pelvic mal-positioning. However, as with the MAG method, it relies on the fixed external theatre floor for controlling operative inclination and, thus, suffers from the same limitations in this regard.

Although the TAL approach displays superior theoretical results, a possible clinical limitation of the TAL approach is that its visibility may be poor during THR. Unlike the theoretical case, perfect TAL version may not be achievable in practice. Epstein et al¹⁷⁸ observed that osteophytes obscured the TAL in 53% (n=34/64) of cases within

their cohort. Failure to identify the TAL intra-operatively will force an orthopaedic surgeon to employ alternative guidance techniques, for example, a MAG. This would negate the advantage of the TAL method. However, with sufficient clearance of osteophytes intra-operatively, Archbold et al²⁶ was able to identify 99.7% (n=997/1000) of the TALs within their cohort. A secondary restraint on the use of the TAL method is the AOV variability (relative to the theatre table longitudinal axis). As illustrated in Figure 3.10, use of the TAL method results in greater AOV variability than the MAG method. This is particularly true if the pelvis is posteriorly / anteriorly tilted or externally/ internally rotated. Due to greater AOV variability, orthopaedic surgeons may be wary of using the TAL approach for which the target angles relative to traditional external landmarks (theatre table) may appear excessive. However, as indicated by Figure 3.11, the TV variability is theoretically zero for a given TAL version. This in turn will reduce overall variability in radiographic acetabular orientation.

In an in-vitro study performed by Grammatopoulos et al¹⁷¹ using a pelvic model, orthopaedic surgeons were asked to align the acetabular component using both the TAL and MAG methods. In their study, for a given TAL version, the mean deviation between the target and true version was found to be less than or equal to 3° for both approaches investigated within this study. As both approaches exhibited a high degree of accuracy, it would suggest that they are interchangeable. This contradicts the findings of this study in which the TAL approach ($TV_{\text{Range}} = 0.0^\circ$), for a given TAL version, was considerably better at reducing TV variability than the MAG method ($TV_{\text{Range}} = 146^\circ$). However, in the study performed by Grammatopoulos et al¹⁷¹, the pelvic model was maintained in a neutral orientation. As such, for their study, the pelvic model TAL version relative to the APP was equivalent to the TAL version

relative to the longitudinal axis of the theatre table and thus the version handle of the MAG at all times. In practice, the pelvis frequently deviates from neutral operative positioning.^{27,193-195} Subsequently, the APP may not be aligned with the longitudinal axis of the theatre table. In this event, as illustrated by this study, use of the MAG approach will result in greater TV variability than the TAL method.

Clinically, use of the TAL over the MAG method has been previously supported within the literature. Meermans et al¹⁷⁶ conducted a study in which two cohorts of THR patients were operated on using either the MAG or TAL approach. They illustrated that use of the TAL (n=40, 2-25°) method for controlling version intra-operatively resulted in significantly reduced variation in 2D radiographic version (RV, measured post-operatively) when compared to the MAG approach (n=40, 2-35°). Although the TAL approach in their study exhibited increased control over radiographic version, it still resulted in considerable variation (RV_{Range}=23°) when compared to the findings of this study (TV_{Range}=0°).

There are two possible explanations for the variability in radiographic version obtained by Meermans et al¹⁷⁶ when using a TAL approach. Firstly, within this study, a single TAL version was used to enable comparison between the TAL and MAG methods. However, in practice, TAL version is patient-specific and subject to considerable variability.²⁶ Consequently, when orientating the acetabular component relative to the TAL intra-operatively, orthopaedic surgeons should expect to see differences in radiographic version that reflect the differences in TAL version between patients. Secondly, the measures of true operative acetabular orientation (relative to the patients pelvis) used in this study are not in the same reference frame as the 2D radiographic measures used by Meermans et al.¹⁷⁶ In addition to patient-specific TAL version, each

patient also has a specific pelvic tilt (angle between the APP and radiographic coronal plane, Figure 2.20) within the radiographic reference frame.²⁸ Radiographic pelvic tilt and native TAL version are co-planar angles that will contribute to the overall cumulative version of the acetabular component relative to the radiographic coronal plane. The degree of pelvic tilt has been shown to impact the degree of radiographic version projected and, to a lesser degree, radiographic inclination.¹⁹⁷ Consequently, even if the surgeon hits the same targets for true acetabular orientation relative to the pelvis for a given cohort, radiographic variability will persist due to the variation in pelvic orientation within the radiographic reference frame.

Whilst posterior / anterior pelvic tilt remained a significant predictor of true acetabular orientation variability for the MAG approach (TV, $p < 0.01$), it was deemed non-significant for the TAL approach (TI, $p = 0.39$). Clinically, when using the TAL approach, this suggests that an orthopaedic surgeon should be primarily concerned with reducing pelvic adduction / abduction and external / internal rotation as a means of minimising the discrepancy between apparent operative and true acetabular orientation. This in turn will reduce radiographic acetabular orientation variation. Within the theoretical range investigated, for both single and combined rotations, pelvic adduction / abduction ($\theta = -0.95$, $\beta = -0.905$) was found to have a stronger influence on changes in TI than external/internal rotation ($\theta = 0.36$, $\beta = 0.318$). Of these two modes of pelvic rotation, this would suggest that pelvic adduction / abduction is of primary concern. However, clinically, the magnitude of pelvic adduction / abduction (-19° to 8°) reported tends to be less than the magnitude of external / internal rotation (-27° to 17°).^{27,193-195} In practice, pelvic external / internal rotation may therefore have a similar impact on TI as adduction / abduction if its magnitude is sufficiently large.

Computer aided orthopaedic surgery (CAOS) may be used to monitor the degree of pelvic adduction / abduction and external / internal rotation intra-operatively. Consequently, CAOS enables the orthopaedic surgeon to obtain their desired true acetabular orientation relative to the operative pelvis and has been shown to reduce the variability in acetabular component placement^{183,184,187} by determining the intra-operative pelvic orientation. This is most accurately achieved using an image-based system that recognises the internal anatomy during THR surgery and then builds a 3D image of the pelvis from this. In contrast, image-free systems are more widely used to build a 3D image by referencing bony landmarks on the pelvis through skin, which in turn introduces errors.¹⁹⁶ Within the United Kingdom, CAOS is used in less than 1% of THR surgeries.¹⁰ This may be due to cost, increased operative time, and lack of published benefit.^{182,215} For example, Lass et al.¹⁸⁸ illustrated no significant difference between the MAG method and an image-free system for controlling TI.

A limitation of this study is the use of a theoretical range alongside a fixed order of rotation for combined pelvic mal-rotations. Due to the nature of combined rotations, without a pre-existing data set, it is hard to quantify which single-axis rotations (their magnitudes and order) are likely to occur. Atypical combinations for pelvic orientation will therefore result in extremes that would otherwise not occur in clinical practice. However, multiple mapping procedures (the order in which the rotations are applied) can be used to obtain the same angular position of the pelvis. The larger ranges for pelvic mal-rotation alongside the mapping procedure provided (Eqn 4) ensured that the majority of clinical pelvic orientations were likely achieved. Future work will seek to isolate true values for clinical pelvic mal-rotation alongside the current mapping procedure in an effort to reduce cases that would not likely occur in practice. A further limitation of the theoretical model is that it may not be intuitive to a surgeon. In

practice, a surgeon will be able to use their experience to avoid extreme orientations. However, an advantage of the theoretical model is that the spatial location of the acetabular component axis relative to the APP and sagittal pelvic plane is known, i.e. the true orientation. This enables differentiation between retroverted and anteverted components, which is not possible on the anterior-posterior X-ray.

3.5 Conclusion

To reduce radiographic acetabular orientation variability, there is a need to reduce the discrepancy in true acetabular orientation resulting from intra-operative pelvic orientation. In this simulated study, the TAL method exhibited greater control over TV when compared to the MAG method. However, with respect to TI, both methods performed poorly when the sagittal pelvic plane was not parallel to the surgical theatre floor. Thus, the use of the TAL approach can be used to reduce radiographic variability, but there is room for improvement with respect to its control over TI. For the TAL approach, pelvic adduction / abduction and external/ internal rotation were found to be significant predictors for changes in TI. In the absence of these modes of rotation, the pelvic sagittal plane will be parallel to the theatre floor. In order to reduce variable acetabular component placement with respect to target orientations, there is an imperative to find an affordable and practical method of ensuring that the sagittal plane of the pelvis is parallel to the theatre floor at the time of acetabular component insertion (Objective 3).



FOUR

Patient Positioning for THR

Overview: In Chapter 3, pelvic external / internal rotation and adduction / abduction were identified as the primary modes of pelvic orientation that contributed to changes in true inclination when using the transverse acetabular ligament approach. Consequently, the primary aim of this chapter was to develop and trial a technique to aid a surgeon in patient positioning with respect to the primary modes of theoretical intra-operative pelvic mal-rotation (**Objective 3**). The secondary objective was to assess the impact of different patient supports and theatre table surfaces on *lateral decubitus* pelvic positioning. The use of transverse pelvic lines and a coronal alignment guide proved capable of monitoring pelvic adduction / abduction and external / internal rotation respectively. The choice of patient support did not significantly influence pelvic orientation during patient positioning and no practical reduction in pelvic mal-rotation was gained by altering the surface of the theatre table. Overall, this technique represents an affordable solution that can be readily implemented without additional radiation exposure.

4.1 Introduction

In Chapter 3 appropriate choice of surgical technique was demonstrated to help reduce errors in acetabular component orientation. In particular, the transverse acetabular ligament (TAL) approach (Figure 1.16) can theoretically eliminate errors in operative version due to pelvic flexion / extension. A benefit of the TAL approach is that it is an affordable, patient-specific technique that can be readily incorporated into current surgical practice without additional surgical props.²⁶ However, a limitation of the TAL approach is it does not act as a suitable landmark for guiding operative inclination. When using the TAL approach, the theatre floor is still used as a substitute for the pelvic sagittal plane. If the pelvic sagittal plane is not parallel to the theatre floor, the angle between the introducer and the theatre floor (apparent operative inclination) is not the same as the angle it makes with the pelvic sagittal plane (true inclination, Figure 3.1). Consequently, the acetabular component can be placed at unknown orientations relative to the pelvis resulting in unexpected radiographic inclinations.

Computer aided orthopaedic surgery (CAOS) was first introduced to monitor intra-operative pelvic positioning and avoid errors in component orientation due to referencing from external, as opposed to anatomical, landmarks. It has been shown to reduce the range of radiographic acetabular component orientations achieved when compared to the previous approaches.^{183-184,187,189-191} Despite this, CAOS is used in less than 1% of orthopaedic surgical procedures within the UK.¹⁰ The main limiting factor for the widespread adoption of CAOS is cost. The cost of the machinery, the associated software, maintenance, increased operating times, and the increase in manpower required are significant burdens.^{179-180,215} Additionally, the literature has indicated that the mean acetabular orientations achieved when using CAOS do not deviate from those

achieved using conventional approaches.¹⁸⁴⁻¹⁸⁷ As such, CAOS has limited advantage over conventional cheaper approaches. With the expected increase in the socioeconomic burden of osteoarthritis,²¹⁶ an opportunity exists to find alternative cost-effective methods that can be used to reduce the range of radiographic acetabular orientations achieved during THR.

From Chapter 3, pelvic external / internal rotation and adduction / abduction were theoretically identified as the primary modes of pelvic orientation that contributed to changes in operative inclination when using a TAL approach. Consequently, the primary aim of this chapter was to develop and trial a technique to aid a surgeon in patient positioning with respect to the primary modes of theoretical intra-operative pelvic mal-rotation (Objective 3). This approach involves the use of transverse pelvic lines drawn on the patient's lower back and a new coronal alignment guide for monitoring pelvic adduction and rotation respectively. The secondary objective was to assess the impact of different patient supports and theatre table surfaces on *lateral decubitus* pelvic positioning.

4.2 Design Process

From chapter 3, it was observed that pelvic adduction/ abduction and internal / external rotation had the greatest impact on true acetabular orientation. As such, the objective became to minimise these pelvic mal-rotations during patient positioning. Through collaborative discussion with an orthopaedic and engineering team, the use of pressure sensors (Tekscan), body motion sensors (Xsens) and or the design of new patient supports was initially considered.

With respect to the pressure sensors, it was hypothesised that the prominent bony ASIS's would exert sufficient force on pressure pads (attached to patient supports), that a subsequent pelvic adduction / abduction could be tracked by relative changes in pressure. However, following a visit to the gait lab at Musgrave Park Hospital, it was decided that the pressure sensors in question lacked sufficient resolution to accurately detect pelvic adduction / abduction. Furthermore, it was feared that a high BMI (an increase in soft tissue) would further compromise the accuracy of the sensors.

Conceptually, multiple body motion sensors could have been attached to a patient relative to their pelvis during surgery and their subsequent changes of motion recorded. They were ruled out following a visit to DePuy (whom owned a set of the sensors) and a discussion that highlighted that the sensors in question were sensitive to large forces as would be expected during total hip replacement. Furthermore, high BMI could further impact their use as motion could be introduced due to loose skin as opposed to pelvic movement.

From a review of current practice (Appendix A), it was observed that new patient supports were unlikely to be readily adopted into current practice; a primary concern was expense. As such, a further design challenge became to design tools that could be readily implemented into current practice without posing a serious financial investment. Following further discussion, the use transverse pelvic lines and a coronal alignment guide for monitoring pelvic adduction and rotation respectively were proposed.

With respect to the transverse pelvic lines for monitoring pelvic adduction, a new custom slotted horizontal ruler was developed (Figure 4.1). With this ruler, three lines

could be drawn across the patients lower back (Figure 4.2) using a standard operative marker whilst sitting in an upright position on a flat surface. A level was attached to the guide to ensure that the lines were being drawn in a neutral manner. Following application of the transverse pelvic lines, a patient would be moved to the lateral decubitus position and the anterior patient supports affixed. It was hypothesised that if the pelvis was abducted / adducted in this position, that the angular position of the transverse pelvic lines would reflect the degree of adduction / abduction. For the purpose of this study, three lines were used so as to determine which line (position relative to the natal cleft) best represented pelvic adduction / abduction. However, in practice a normal ruler could be adopted. Pelvic adduction / abduction could then be counteracted by adjusting the head down angle of the theatre table (planar motion to adduction / abduction) such that the transverse pelvic lines became perfectly vertical in the lateral decubitus position. This could be assisted via the use of a plumb line.

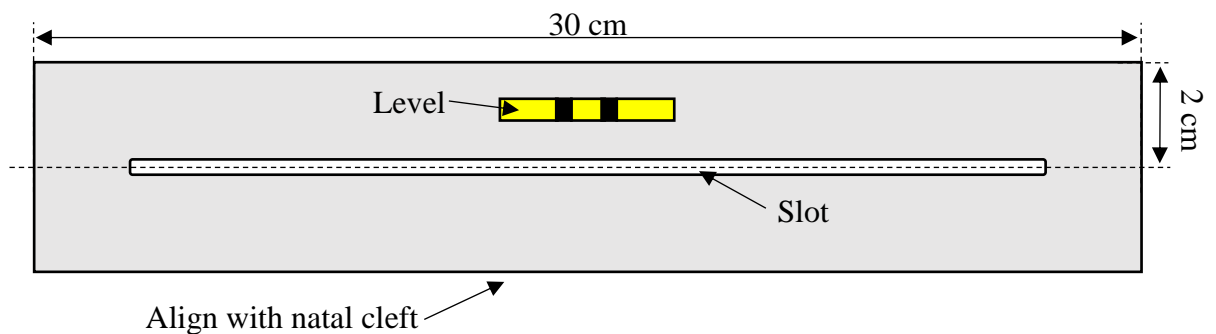


Figure 4.1 Slotted horizontal guide for drawing transverse pelvic lines in the upright seated position. With the bottom edge of the guide aligned with the top of the natal cleft (patient sitting upright on a flat surface), three lines can be drawn: line one along the superior edge of the horizontal guide, line 2 through the middle slot of the horizontal guide and line 3 along the inferior edge of the horizontal guide.

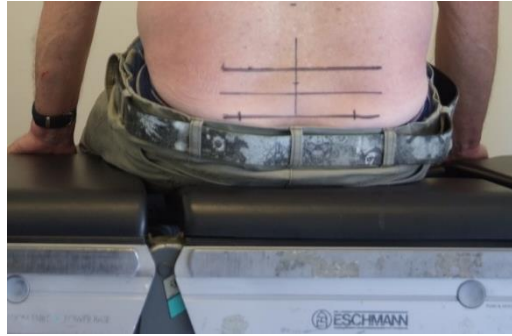


Figure 4.2 Transverse pelvic lines drawn across the participants lower back in sitting.

It was hypothesised that pelvic external / internal rotation could be monitored during patient positioning via the use of a new custom the coronal alignment guide (Figure 4.3). In the lateral decubitus position, following alignment of the ASIS's with the anterior patient supports, the spherical ends of the coronal alignment guide can be placed against a patient's lower back such that the handle of the coronal alignment guide crosses the spine (approximately at a right angle) and its spherical ends remain approximately equidistant to the spine. A level attached to the upper arm of the coronal alignment guide can then be used to track the degree of pelvic external / internal rotation. Pelvic external / internal rotation can then be counteracted by ensuring that the level is neutral.

4.3 Method

A clinical study was undertaken to determine the extent by which the pelvis differs from true pre-operative lateral decubitus using different surgical hip props and surfaces. Participants were divided into three groups (Table 4.1): pre-operative THR patients (PO group), age-matched control participants who had no pre-existing joint replacements or severe joint complaints (OC group), and younger control participants who weren't age-matched to the pre-operative group (YC group). Like the age-

matched control group, the younger controls were also excluded if they had pre-existing joint replacements or severe joint complaints. All candidates who had a known leg length discrepancy were also excluded. These groups were chosen to see if either age or the presence of comorbidities (joint complaints and or replacements) impacted the use of the coronal alignment guide and transverse pelvic lines.

Table 4.1 Summary of study groupings.

PO group	Pre-operative THR patients with no perceived leg length discrepancy
OC group	Age-matched control subjects who had no joint replacements, no severe joint complaints, and no perceived leg length discrepancy
YC group	Younger control subjects who had no joint replacements, no severe joint complaints, and no perceived leg length discrepancy

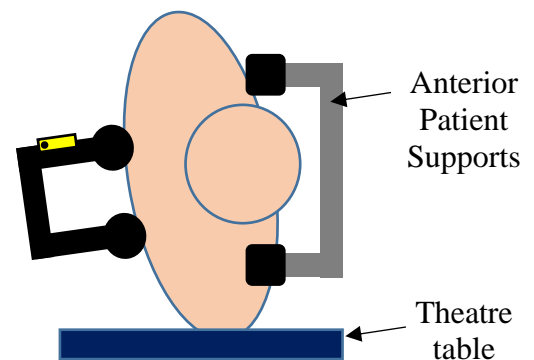


Figure 4.3 Coronal alignment guide used to achieve neutral pelvic rotation when patient is positioned in lateral decubitus.

To address the primary study objective, transverse pelvic lines were first drawn across each participant's lower back to provide a potential reference for monitoring pelvic adduction / abduction (Figure 4.2). To assess the validity of the lines for monitoring pelvic adduction, participants were asked to undergo two tasks: an imposed leg length imbalance and lateral trunk flexion (Figure 4.4). A leg length imbalance was introduced by asking the participants to stand with a block under one foot whilst their other foot was kept on the ground. This was repeated for the other foot and for different sizes of blocks (10mm, 25mm and 35mm). It was hypothesised that the transverse pelvic lines would become increasingly adducted with greater imposed leg length imbalances and remain neutral during lateral trunk flexion.

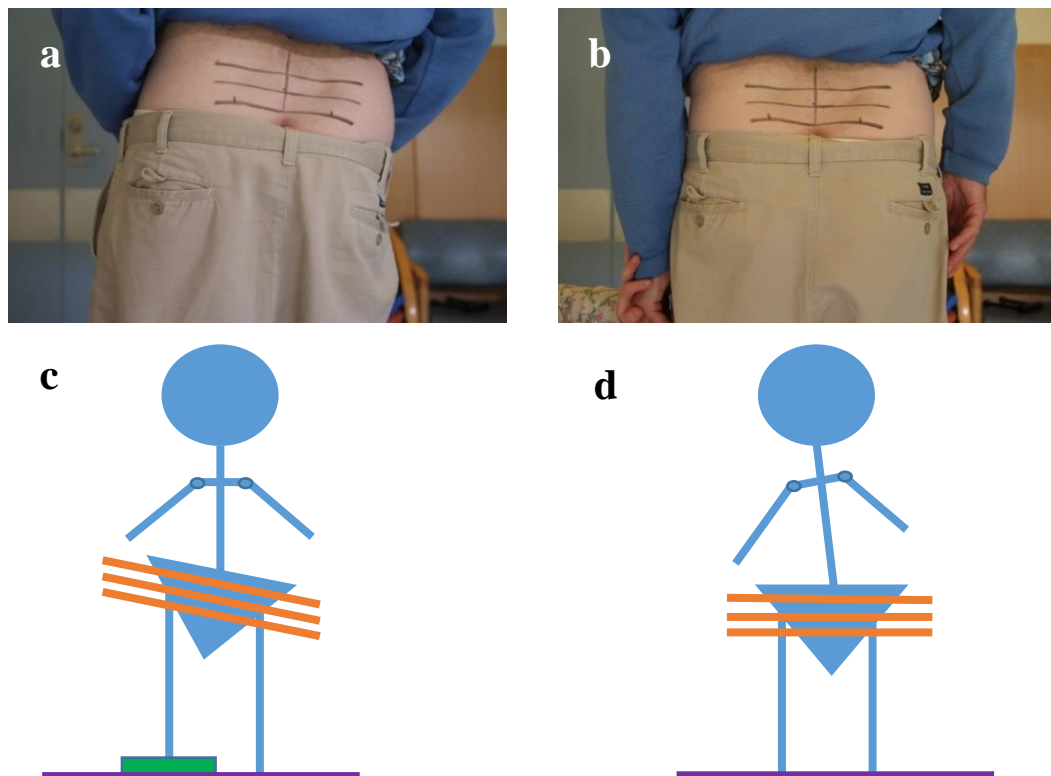


Figure 4.4 Transverse pelvic lines during imposed leg length imbalance (a & c) and lateral trunk flexion (b & d).

With respect to pelvic internal / external rotation, a coronal alignment guide was used to place each participant in the *lateral decubitus* position (on their side) on three different surfaces without supports: a standard operating table surface, a six-inch (0.15 m) foam mattress on top of an operating table, and a hard mattress on top of an operating table. Three different surfaces were used to see if the degree of softness of the operating table surface impacted the degree of pelvic mal-rotation during patient positioning. For each surface, a digital inclinometer (Digi-Pas®, DWL-80E) was placed on the upper arm of the guide to get a measure of pelvic rotation about the longitudinal axis. It was hypothesised that the coronal alignment guide would enable the study investigator to achieve neutral pelvic rotation, as observed by digital inclinometer readings following participant positioning.

To address the secondary objective (assessing the impact of different patient supports and theatre table surfaces on lateral decubitus pelvic positioning), three surfaces were used as previously described. Two different types of surgical patient support (Figure 4.5) were investigated: (a) a single anterior superior iliac spine (ASIS) post and (b) a double ASIS post (Universal Lateral Positioner System, Innovative Medical Products®, USA, 2014). With the single ASIS support, each subject was approximately aligned in the lateral decubitus position on the surgical table. Following this, the single ASIS support was extended until it engaged the upper ASIS of the subject (on the operative hip side in practice). For the double ASIS support, the supports were first attached to the surgical table. Each subject was then rolled into the lateral decubitus position such that their respective ASIS's engaged both of the ASIS supports.

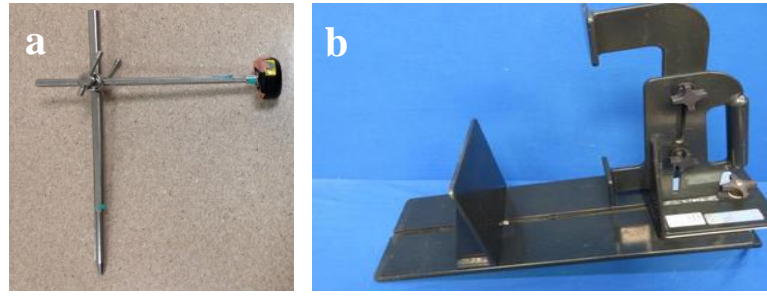


Figure 4.5 a) Single ASIS post b) Double ASIS post.

4.3.1 Participant Recruitment and Experimental Design

Each group was to consist of 34 participants following a sample size calculation based on the findings of a pilot study containing 12 volunteers. As the pilot study did not include the entirety of the experimental procedure for both aims, measures for these candidates were excluded from analysis thereafter.

Prior to recruitment, ethical approval for this study was obtained from the Office for Research Ethics Committees Northern Ireland (14/NE/1163). The participant information sheets and consent forms for all groups are included in Appendix C. Participants within the PO group were recruited by telephone from the Primary Joint Unit at Musgrave Park Hospital (MPH) by a study investigator prior to their clinical appointments. At the time of recruitment, patients from the PO group were preparing to undergo THR under the care of Professor David Beverland or Mr Dennis Molloy (both of the Primary Joint Unit at MPH). Control participants were contacted via word of mouth or through posters located at Queen's University Belfast and MPH in accordance with requirements of the ethical approval. All experimental work was undertaken at MPH. The inclusion criteria for all participants were that they

- be aged between 21 and 80,
- have a BMI within the range of 18 to 29.9,

- be able to stand for a period of 5 min at a time and stand on a block (10-35 mm) without the aid of a walking stick,
- be able to get onto an operating table (with assistance) and lie on their side, and
- be capable of giving informed consent.

4.3.2 Experimental Method

For the duration of the study, all participants were asked to remove their shoes prior to any measurements being made. Participant demographics and experimental measures were recorded using a case report form (Appendix C). Each participant's weight, height, inter ASIS distance, age, and gender were recorded. At each stage of the study, photographs were taken to enable analysis of the transverse pelvic lines. ImageJ²¹⁷ was used to determine the magnitude of pelvic abduction (+) / adduction (-) from these photos. Positive measures of abduction are defined in Figure 4.6.

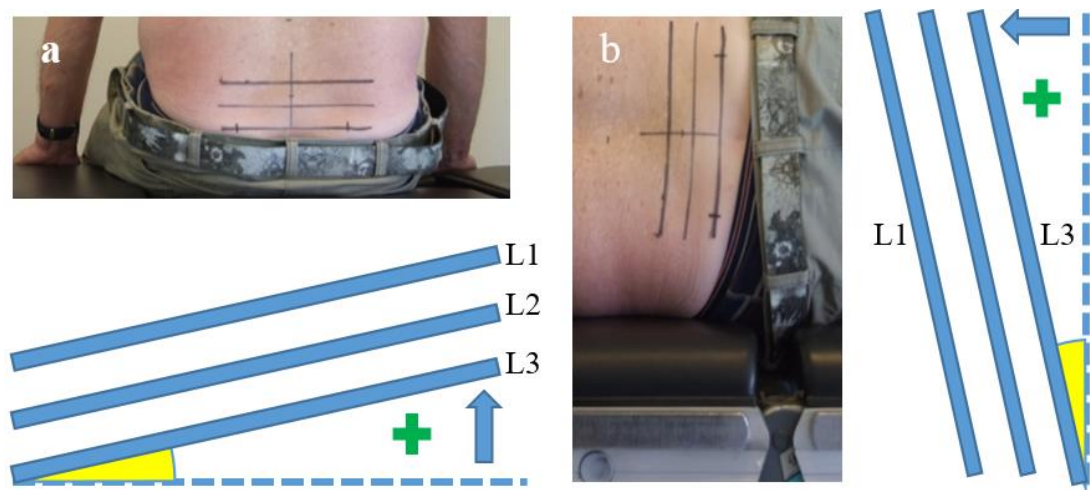


Figure 4.6 Transverse pelvic lines in a) sitting/standing and in b) lateral decubitus position for a right operative hip. Directions constituting positive measures of abduction are indicated in the accompanying schematic for each position.

As mentioned earlier, the first stage of the study involved drawing transverse pelvic lines. With the surgical table level, the participants were asked to sit upright on the table with their legs hanging over the side (Figure 4.2). A digital inclinometer (Digi-Pas®, DWL-80E) was used to ensure that each segment of the surgical operating table was level for each case. In this position, the transverse pelvic lines were drawn. A slotted horizontal guide was used to draw the transverse pelvic lines. With the bottom edge of the guide aligned with the top of the natal cleft, four lines were drawn in total: line one was drawn along the superior edge of the horizontal guide, line 2 was drawn through the middle slot of the horizontal guide, line 3 was drawn along the inferior edge of the horizontal guide, and line 4 was drawn perpendicular to the previous lines in the paravertebral region.

To establish the validity of the transverse pelvic lines for monitoring pelvic adduction, a photograph was initially taken of each participant in neutral standing, i.e. no imposed leg length imbalance or lateral trunk flexion. Leg length imbalances were then imposed by placing blocks of different heights (10 mm, 25 mm, 35 mm) under one of the participant's feet. This was repeated for the other foot to check for potential natural leg length imbalance or asymmetric abduction for each participant. Blocks were increased in size until the participant could no longer maintain a straight leg on the unimpeded side. Consequently, not all participants have measurements for all three blocks. The purpose of the blocks was to assess the ability of the lines to move with pelvic adduction / abduction. The imposed leg length aspect of the study was followed by lateral trunk flexion. With both feet on the ground, each participant was asked to slide their hand down their side whilst maintaining a straight back. This was repeated for the contra-lateral side. The purpose of lateral trunk flexion was to assess the ability

of the lines to remain neutral with the pelvis whilst other body movements were being undertaken.

To assess the validity of the coronal alignment guide, each participant was arranged in the *lateral decubitus* position on each of the three surfaces (standard, hard, memory foam) without patient supports using the coronal alignment guide. A measure of the alignment guides ability to achieve neutral pelvic rotation was recorded using a digital inclinometer at this stage as described previously. It was tested on different surfaces relative to the standard operating surface to asses if table surface would impact the guides ability to achieve neutral pelvic rotation. External rotation about the longitudinal axis was regarded as positive and internal rotation was treated as negative (Figure 4.7). When positioning the PO group into *lateral decubitus*, their operative hip was placed superiorly to their non-operative hip. For both control groups, the superior hip side was chosen to reflect those of the PO group.

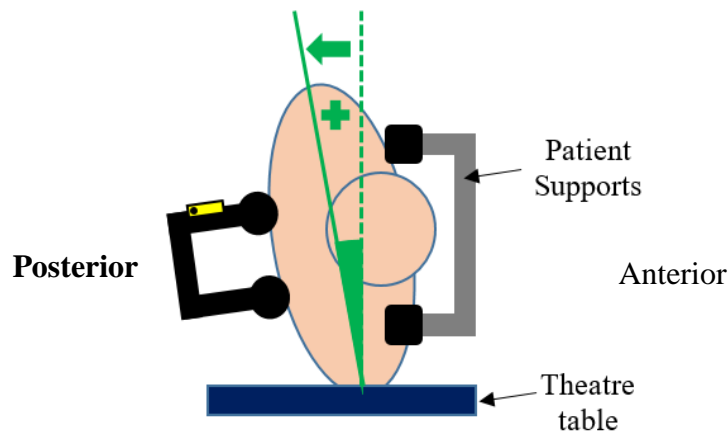


Figure 4.7 External rotation of the pelvis was regarded as positive whilst internal rotation was regarded as negative.

Whilst in the *lateral decubitus* position, the single ASIS patient support was attached as would occur in practice. In each instance, the single ASIS support was engaged with

the superior ASIS. The coronal alignment guide was then placed relative to the participant position and the digital inclinometer was used to measure the rotation that resulted from the use of the single ASIS support. This procedure was then repeated for the double ASIS post on the standard surgical theatre table. For the double post design, the lower ASIS was palpated and aligned with the lower post. The participant was then rolled until their top ASIS was in contact with the top post. The height between the posts could be adjusted to account for differences in inter-ASIS distance, but the faces of the posts were maintained level to each other. Different surgical supports were employed to assess whether the use of different styles of surgical supports impacted the degree of pelvic malrotation.

Following the standard surgical theatre surface, the above procedure (single ASIS support, double ASIS support) was repeated for the hard surface. With respect to the memory foam mattress, its dimensions did not permit the use of the patient supports. As such, a single measure of the investigators ability to obtain neutral pelvic rotation on this surface was measured alongside the degree of pelvic adduction that resulted from this surface alone.

4.3.3 Analysis

All analysis was carried out using the R statistical programming language²¹⁸ and MATLAB (version 2016b, MathWorks Inc., USA). Due to the volume of different analyses required, some details are described within the corresponding result sections.

With respect to pelvic adduction / abduction, for the different aspects of the study, analysis was performed using the measures of pelvic adduction / abduction from a single transverse pelvic line. This was done to simplify the resultant analysis. The use

of a single transverse pelvic line for analysis was validated using pairwise correlation (to ascertain that the TPL's retained the same angular orientation and spacing).

Linear mixed effects analysis was used to investigate significant effects (assumed to be $p < 0.05$) due to variation in the explanatory variables for each of the dependant variables investigated (pelvic rotation or adduction). Linear mixed effects analysis divides contributing factors into fixed and random effects. Fixed effects are those that would be considered to impact the mean response, whilst random effects contribute to the observed variance. Random effects often result from pseudo-replication (repeated sampling of participants). Although multi-factor ANOVA with repeated measures can also be used to analyse repeated sampling of participants, linear mixed-effects analysis is more robust for unbalanced groups, as was the case for this study.²¹⁹ For all linear mixed effects analyses, "Subject ID" was treated as a single random effect. This was to account for variability that resulted from subject-specific factors and repeated testing. Linear mixed effects analysis was conducted using the `lme4`²²⁰ package for the R statistical computing language. Post-hoc analysis of differences in least squares means was computed when necessary using the `lsmeans` package²²¹ for R.

4.4 Results

Originally the study had planned to include 34 participants in each of the groups. However, only the PO group reached its target recruitment. Recruiting participants that met the inclusion for the OC group (no previous joint replacements or severe joint complaints) proved particularly difficult. In order to complete the study by the end date of the thesis, lesser numbers had to be used. A total of 70 participants were recruited in total across the three groups (Table 4.2). Although less than the target number, the size of each group was sufficient for statistical analysis.

4.4.1 Identifying a Preferred Transverse Pelvic Line to Monitor Adduction

Pairwise correlations between the angles of each line with respect to each other during adduction revealed strong correlations between all three lines and their degree of pelvic adduction across all stages of the study ($n = 1079$, Figure 4.8). This highlighted that the transverse pelvic lines retained the same corresponding angular orientation and thus one transverse pelvic line could be used as a reference measurement.

Table 4.2 Summary of Participant Demographics (Mean \pm SD (min to max))

Group	F*	M*	Age (Years)	BMI (Kg / m ²)	Inter-ASIS (cm)
PO (n=34)	14	20	67.2 \pm 8.64 (41 to 78)	26.7 \pm 2.88 (20.7 to 34.0)	24.2 \pm 1.91 (19.9 to 28.1)
OC (n=13)	6	7	60.5 \pm 4.99 (56 to 70)	23.5 \pm 3.69 (22.3 to 33.5)	21.5 \pm 2.56 (17.4 to 25.9)
YC (n=23)	9	14	25.9 \pm 3.36 (22 to 34)	23.4 \pm 3.24 (18.6 to 30.3)	21.8 \pm 1.96 (18.2 to 26.4)

*F=Female, M=Male

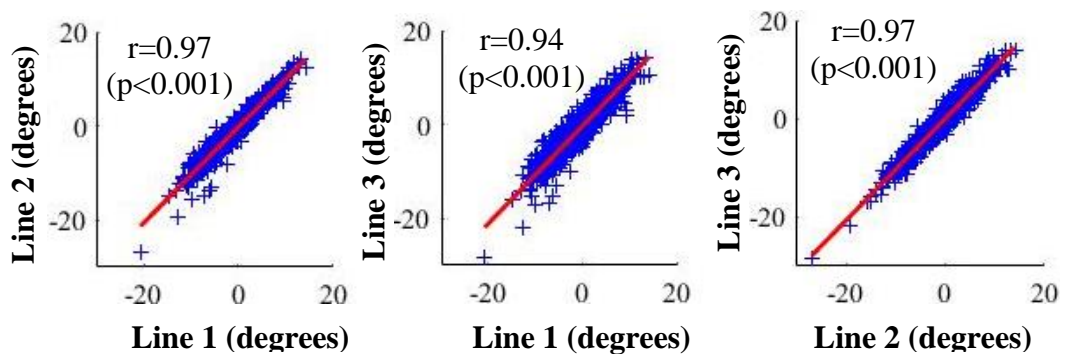


Figure 4.8 Strong positive correlations for measures of adduction were observed between all three transverse pelvic lines.

It was hypothesised that, if a participant underwent lateral trunk flexion, their transverse pelvic lines would remain neutral (i.e. no change in adduction). Measures for the deviation from neutral whilst undergoing lateral trunk flexion were obtained by

subtracting the measure of adduction in standing (i.e. with no block) from those observed during lateral trunk flexion. As lateral trunk flexion was repeated for both sides, the overall adduction deviation was counted as the sum of the absolute adduction deviations on each side. No significant differences were observed across the three lines for measures of absolute adduction deviation during lateral trunk flexion ($p=0.392$, $n=70$). Despite this, a small degree of angular separation during lateral trunk flexion was observed. The range observed for line 3 (Table 4.3) was the lowest and thus for subsequent analyses, line 3 alone was used for all comparisons relating to adduction.

Table 4.3 Absolute deviation between measures of adduction (AAD) across transverse pelvic lines during lateral trunk flexion (Mean \pm SD (Min to Max)).

	Line 1	Line 2	Line 3
AAD (degrees)	4.01° \pm 2.17° (0.11° to 9.82°)	3.37° \pm 1.82° (0.43° to 9.39°)	3.09° \pm 1.47° (0.44° to 7.03°)

4.4.2 Neutral rotation using the coronal alignment guide

Without supports, a measure of the alignment guides ability to achieve neutral pelvic rotation was recorded using a digital inclinometer. Analysis of rotation as a function of group (PO, OC, and YC) and surface (normal theatre surface, hard, and memory foam) alongside their possible interactions did not find significant differences between groups (PO, OC or YC, $p=0.29$) or across surfaces ($p=0.31$). The choice of surface did not impede the ability to control pelvic rotation. Furthermore, low overall mean external pelvic rotation of 0.60° \pm 0.68° (−3.30° to 6.10°) was observed when using the coronal alignment guide to achieve neutral pelvic rotation (Table 4.4). Thus, a high degree of accuracy was typically achieved when using the guide. Of note, despite no

significant differences being found between surfaces, both of the extreme measurements (-3.30° and 6.10°) belonged to the hard surface grouping.

Table 4.4 Measures of rotation across surfaces without patient supports using the coronal alignment guide. The pelvis tended to be slightly externally rotated (positive).

	Normal	Hard	Memory
Rotation (degrees)	$0.60^\circ \pm 0.52^\circ$ (-0.90° to 1.70°)	$0.72^\circ \pm 0.93^\circ$ (-3.30° to 6.10°)	$0.47^\circ \pm 0.48^\circ$ (-1.00° to 1.60°)

4.4.3 Adduction across different blocks whilst standing

Measuring the change in orientation of the lines while standing on blocks was performed to test the ability of the transverse pelvic lines to monitor pelvic adduction (Table 4.5). Pelvic adduction / abduction can result in a loss of acetabular coverage for a given apparent intra-operative target acetabular orientation. Stepwise reduction of a linear mixed effects model investigating the effect of group, block side and block height, including potential interactions and treating repeated measures per subject as a random effect, resulted in a minimal model that indicated significant effects for block height ($p < 0.001$), and the interaction of group with side ($p < 0.001$).

Table 4.5 Measures of pelvic adduction (degrees) across block height.

	Neutral	10 mm	25 mm	35 mm
Mean	-0.12°	2.17°	5.62°	8.09°
SD	2.96°	2.99°	3.22°	3.01°
Min	-6.53°	-6.77°	-5.11°	0.19°
Max	6.06°	10.1°	12.8°	14.0°

Post-hoc analysis of differences in least squares means between combinations of explanatory variables indicated that only specific contrasts were significant for the interaction of group with block side (Table 4.6). Conversely, significant differences were observed between all block heights ($p < 0.001$, Figure 4.9). There was a linear trend (Figure 4.9) of increased pelvic adduction with increased block height (**Error! Reference source not found.**), which supports the hypothesis that the transverse pelvic lines move with pelvic adduction.

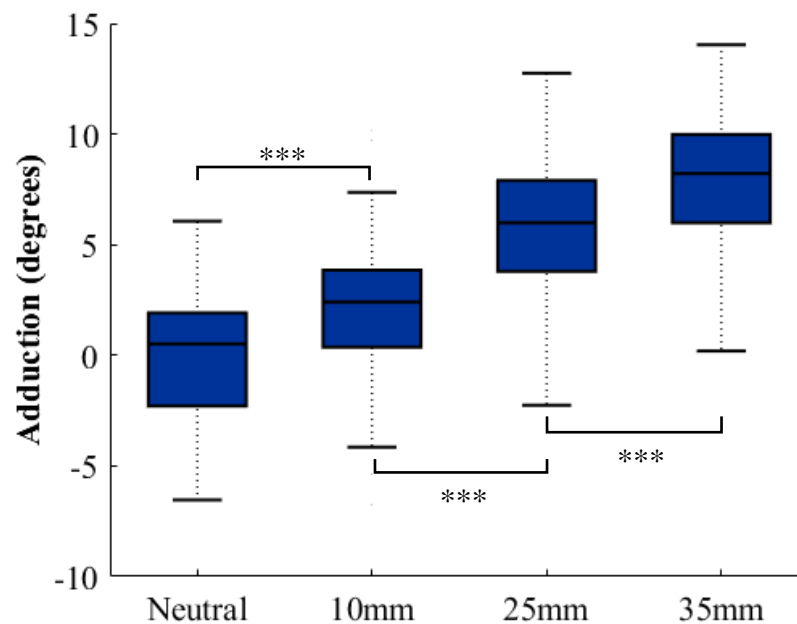


Figure 4.9 Significant differences were observed between all block heights and the magnitude of pelvic adduction whilst standing, supporting the hypothesis that the transverse pelvic lines move with pelvic adduction (***) ($p < 0.001$).

Low correlation was observed between the neutral angle of adduction measured in sitting and that obtained in standing ($r^2 = 0.20$, $n = 70$). The range observed for line adduction was greater in standing (-6.06° to 6.53°) than it was in the sitting position (-1.75° to 5.03° , Figure 4.10). A measure of subsidence was defined as the absolute difference between the adduction in sitting and that in standing. The mean subsidence

was $2.45^{\circ} \pm 1.87^{\circ}$ (0.00° to 9.22°); the worst two cases are presented in

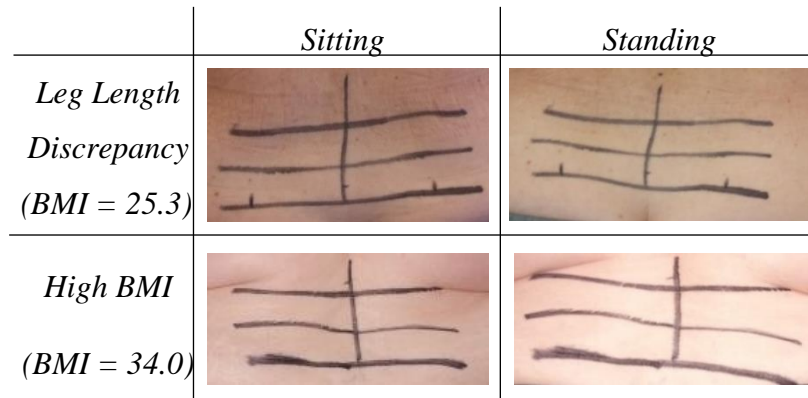


Figure 4.11. Possible factors that may contribute to the variation in neutral measures of adduction between sitting and standing positions are a high BMI and the presence of a previously undiagnosed leg length discrepancy / fixed pelvic adduction in standing. Overall, BMI displayed low correlation with the measures of angular subsidence ($r^2 = 0.14$, $n = 70$).

Table 4.6 Post-hoc analysis of differences in least squares means between combinations of group (PO, OC, YC) and block side (L or R)

CONTRAST	ESTIMATE	SE	DF	T RATIO	P VALUE
L,OC - R,OC	-0.33	0.72	329	-0.46	0.99
L,OC - L,PO	0.02	0.64	329	0.03	1.00
L,OC - R,PO	1.97	0.64	329	3.09	0.03
L,OC - L,YC	1.32	0.62	329	2.14	0.27
L,OC - R,YC	-0.71	0.62	329	-1.16	0.86
R,OC - L,PO	0.35	0.63	329	0.55	0.99
R,OC - R,PO	2.30	0.64	329	3.61	<0.01
R,OC - L,YC	1.65	0.62	329	2.68	0.08
R,OC - R,YC	-0.38	0.62	329	-0.62	0.99
L,PO - R,PO	1.95	0.52	329	3.76	<0.01
L,PO - L,YC	1.30	0.52	329	2.53	0.12
L,PO - R,YC	-0.73	0.52	329	-1.41	0.72
R,PO - L,YC	-0.65	0.52	329	-1.26	0.81

R,PO - R,YC	-2.69	0.52	329	-5.18	<0.01
L,YC - R,YC	-2.04	0.50	329	-4.11	<0.01

*SE – Standard Error *DF – Degrees of freedom

From the literature, natural leg discrepancies can prevail in upwards of 90% of the population.²²² To assess if the subsidence observed could be explained by natural leg length imbalances, theoretical boundaries were determined for allowable angular subsidence. To evaluate these boundaries, two sources of data were acquired from the literature. Firstly, the expected average leg length discrepancy²²² (5.2 ± 4.1 mm) and secondly, the average distance between femoral heads²²³ (17.8cm). From this analysis it was observed that 95.7% ($n = 67/70$) of participants' angular subsidence between sitting and standing fell within three standard deviations of natural leg length discrepancy (

Table 4.7).

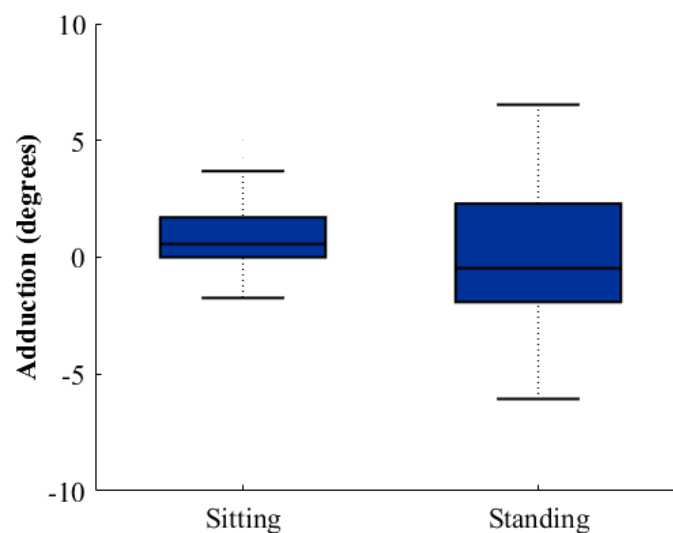


Figure 4.10 The range observed for neutral line adduction was greater in standing than it was in sitting. Angular subsidence was apparent between the two positions

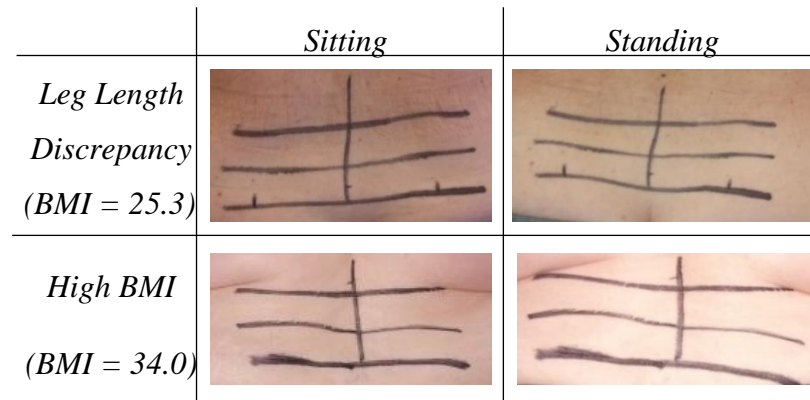


Figure 4.11 Deviation of neutral adduction between sitting and standing. The presence of a leg length discrepancy or a high BMI are possible contributing factors.

Table 4.7 Boundaries for allowable angular subsidence for a given leg length discrepancy (LLD): 95.7% ($n = 67/70$) of participants' angular subsidence between sitting and standing were within three standard deviations of expected average leg length discrepancy.

LLD (mm)	Boundary (Degrees)	No. Participants within Boundary
5.2±4.1 (1SD)	0.35 to 2.99	64.3% (n=45/70)
5.2±8.2 (2 SD)	-0.97 to 4.31	92.9% (n=65/70)
5.2±12.3 (3 SD)	-2.29 to 5.63	95.7% (n=67/70)

4.4.4 Adduction and rotation across different surfaces with different patient supports

For adduction, with respect to Group (PO, OC or YC), surface (normal theatre table or hard), and patient supports (single or double ASIS support), stepwise reduction of

a linear mixed effects model resulted in a minimal model that indicated significant effects for surface (hard and normal, $p < 0.001$) and group ($p < 0.001$).

Post-hoc analysis of differences in least squares means between groups indicated that only the YC group was considered to be significantly different from the PO group ($p < 0.001$). Overall, the pelvis tended to be negatively adducted (lowering of the operative hip) during patient positioning ($-3.55^\circ \pm 4.16^\circ$, -21.9° to 7.90° , Table 4.8, Figure 4.12). Although, the use of the hard surface was found to reduce the degree of pelvic adduction observed, the amount saved was marginal (Table 4.8). Consequently, neither a change in the type of surgical prop or surface helped to dramatically reduce errors in pelvic adduction.

Table 4.8 Summary of pelvic adduction observed across surfaces and between groups (Mean \pm SD (Min to Max)).

	Norm	Hard
PO	$-5.78^\circ \pm 4.48^\circ$ (-21.9° to 7.46°)	$-4.79^\circ \pm 3.82^\circ$ (-15.3° to 7.30°)
OC	$-3.59^\circ \pm 3.19^\circ$ (-10.5° to 3.69°)	$-2.53^\circ \pm 2.85^\circ$ (-8.19° to 1.98°)
YC	$-1.98^\circ \pm 3.55^\circ$ (-9.56° to 6.65°)	$-0.55^\circ \pm 3.27^\circ$ (-6.84° to 7.89°)

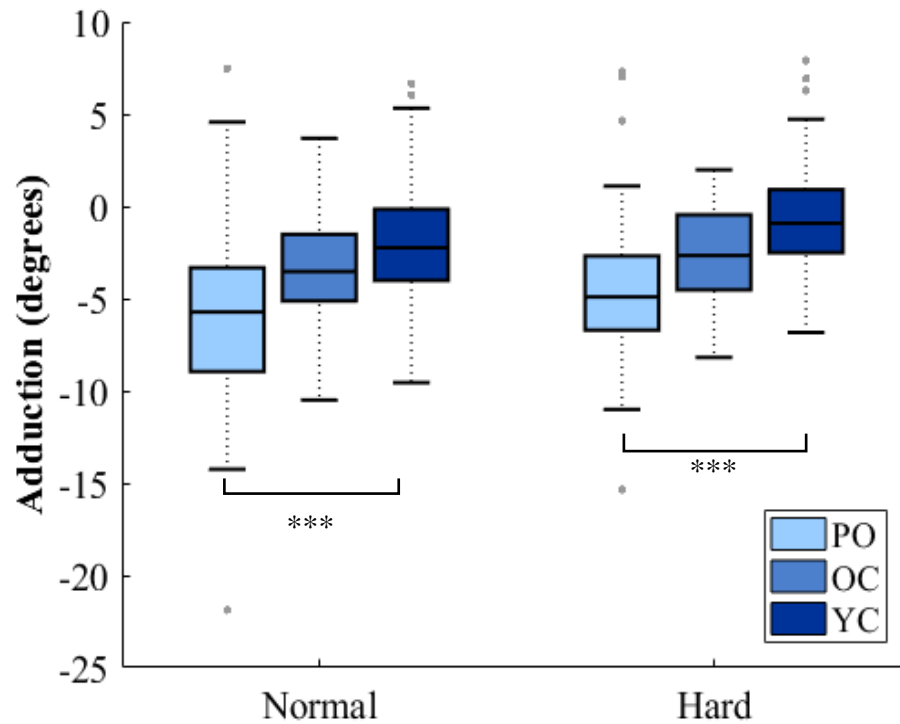


Figure 4.12 Post-hoc analysis of differences in least squares means between combinations of explanatory variables indicated that contrasts were significant between the YC and PO group (***) ($p < 0.001$).

No significant effects on rotation were indicated for patient supports, group, surface, or their interactions. A mean overall internal pelvic rotation of $-2.41^\circ \pm 3.85^\circ$ (-19.0° to 7.90°) was observed. As with adduction, neither a change in the type of surgical prop or surface helped to reduce errors in pelvic rotation.

4.5 Discussion

The primary aim of this chapter was to develop and trial a technique to aid a surgeon in patient positioning with respect to the primary modes of theoretical intra-operative pelvic mal-rotation (adduction / abduction and external / internal rotation, Objective 3). A clear trend of increased pelvic adduction with increased block height was obtained, indicating that the transverse pelvic lines move with pelvic adduction/

abduction (Figure 4.9). With respect to the coronal alignment guide for monitoring pelvic external / internal rotation, a low mean external pelvic rotation of $0.60^{\circ} \pm 0.68^{\circ}$ was observed, highlighting the ability to achieve neutral pelvic rotation when using the guide (Table 4.4).

The secondary aim of this study was to assess the impact of different patient supports and theatre table surfaces on *lateral decubitus* pelvic positioning. With respect to patient supports, no significant differences were observed between supports for measures of pelvic external / internal rotation and adduction / abduction. In this instance, the choice of support did not influence pelvic mal-alignment. With respect to theatre table surfaces and measures of pelvic external / internal rotation, no significant differences were obtained. Conversely, significant differences were observed between theatre table surfaces and between groups (PO and YC) for measures of pelvic adduction / abduction. Although significant differences between surfaces were observed for measures of pelvic adduction / abduction, the mean difference was low ($\bar{x}=1.15^{\circ} \pm 2.91^{\circ}$). Thus, little practical difference would be achieved by altering the surface type of the theatre table.

There are a limited number of studies that quantify pelvic orientation in the *lateral decubitus* position during patient positioning.^{27,193-195} In this study, it was observed that the pelvis tended to be adducted (lowering of the operative hip) during patient positioning in *lateral decubitus*, which supports the aforementioned literature. The degree of pelvic adduction obtained in this study ($\bar{x} = -3.55^{\circ} \pm 4.16^{\circ}$, -21.9° to 7.90°) reflects the clinical measures of pelvic adduction obtained by Grammatopoulos et al²⁷ during patient positioning ($\bar{x} = -4.00^{\circ} \pm 3.00^{\circ}$, -19.0° to 8.00°). This further supports

the use of the transverse pelvic lines for monitoring pelvic adduction during patient positioning.

In this study, it was observed that the pelvis tended to be internally rotated (forward roll) during patient positioning in *lateral decubitus* ($\bar{x} = -2.41^\circ \pm 3.85^\circ$, -19° to 7.9°), which has also been observed in similar studies.^{27,193-195} The degree of pelvic internal rotation obtained in this study reflects the measures of pelvic internal rotation obtained by Kanazawa et al ($\bar{x} = -3 \pm 4.80^\circ$, -17.0° to 7.0°).¹⁹⁵ Conversely, a larger range for pelvic internal rotation was observed by Grammatopoulos et al²⁷ ($\bar{x} = -8.00^\circ \pm 3.50^\circ$, -27° to 4.00°).¹⁸ However, Grammatopoulos et al²⁷ also observed significant differences between orthopaedic surgeons and their ability to achieve neutral patient positioning. Thus, differences between measures of pelvic orientation from this study and those observed by others may be due to different patient positioning practices.

Within this study, no significant differences were observed between patient supports (single and double ASIS support) for measures of pelvic rotation and adduction during initial patient positioning in *lateral decubitus*. In contrast, Grammatopoulos et al²⁷ reported significant differences between similar supports for measures of pelvic external / internal rotation. One reason for the difference between studies may be that further mal-alignment of the pelvis could result from forces applied intra-operatively. For example, intra-operative pelvic motions of up to 31.3° have been reported following patient positioning.^{27,193-195} Thus, the use of double ASIS supports may be better suited to maintaining pelvic neutrality intra-operatively. This is supported by Grammatopoulos et al's²⁷ findings, which identified a significant reduction in intra-operative pelvic movement when using double ASIS supports.

A limitation of the study was that participant positioning was conducted by a physiotherapist and not an orthopaedic surgeon. However, the physiotherapist was initially trained in patient positioning by an experienced orthopaedic surgeon. Secondly, due to the nature of the transverse pelvic lines, a back support could not be added until after adjustments have been made for pelvic adduction during patient positioning. Additionally, a large degree of variability in adduction was observed during imposed leg length imbalances. Despite this large variability and the lack of back supports, the measures of adduction achieved in lateral decubitus positioning strongly reflected those obtained by Grammatopoulos et al²⁷, who used back supports. It was postulated that the variability observed during imposed leg length imbalances are the result of participant-specific leg length discrepancies and differences in inter joint distances. Although a perceived leg length imbalance was an exclusion criteria for this study, natural leg discrepancies can prevail in upwards of 90% of the population.²²² This reinforces the need to draw the transverse pelvic lines whilst sitting, rather than standing, as was the practice of this study to eliminate the impact of a leg length discrepancy and to increase precision. A further limitation is that the true measure of rotation and adduction could not be determined relative to the bony pelvis. This would have required a large volume of radiographs per participant (n = 17) and resulted in harmful and unnecessary radiation exposure. A possible limitation is the impact of the camera position relative to the subject. This could potentially impact the orientation of the lines projected onto the photographic plane. To reduce the impact of inter-subject variability due to camera position, the location of the camera relative to the blocks and surgical table was fixed by a point on the floor which had been marked out using tape at the beginning of the study. Finally, the approach may not be used to monitor intra-operative pelvic orientation due to the use of intra-

operative drapes. However, a large proportion of pelvic mal-alignment is accumulated during patient positioning.^{27,195} Minimisation of pelvic mal-orientation during patient positioning can thus contribute to reduce the impact of mal-aligned pelvis on acetabular component orientation overall.

Future work with respect to this approach could potentially include a study in which patients undergoing their pre-operative radiographs have a photograph taken simultaneously of their lower back on which the transverse pelvic lines have been drawn. In this instance, the radiographs would have to be taken in the standing position which is contradictory to the routine supine radiographs currently used at MPH. Alternatively, radiographic outcomes for this approach could be compared with standard practice approach for measures of radiographic acetabular orientation.

4.6 Conclusion

In conclusion, transverse pelvic lines and a coronal alignment guide may be used to minimise pelvic mal-rotation during patient positioning. This technique does not require the use of additional expensive tools or radiation exposure. The transverse lines can be drawn using a standard skin marker that is already used when the limb is being marked prior to THR surgery. Pelvic adduction can then be neutralised by altering the head down angle of the electronic theatre table (the surgical table is tilted such that a subjects head becomes closer to the ground and their feet become raised relative to their head). Although the coronal alignment guide was custom-made for this study, alternative mechanisms may suffice. For example, a mobile phone with a gyroscope application placed within a sterilisation bag against the lower back may be used to monitor pelvic rotation during patient positioning. This approach presents an

opportunity for reducing outliers in radiographic acetabular orientation as a result of pelvic positioning.



FIVE

Acetabular Component Orientation due to Radiographic Pelvic Orientation

Overview: Radiographic pelvic orientation has been shown to impact the degree of 2D radiographic acetabular orientation. To enable comparisons between patients and to evaluate the use of the transverse pelvic lines (Chapter 4), a common radiographic reference frame of measurement is needed. A computational tool was developed that could be used to reconstruct the true orientation of the acetabular component and pelvis relative to the radiographic coronal plane (Objective 4). The computational tool was applied to a clinical cohort. Unlike version, a small fraction (22%) of the variation between apparent operative and true inclination was accounted for by pelvic radiographic positioning and magnification errors. The remaining variation is solely a function of operative pelvic positioning. Although the transverse pelvic lines reduced the number of outliers, their use didn't significantly alter the mean true acetabular orientation achieved when compared to standard practice. A key clinical finding was that operative pelvic adduction is minimal and thus pelvic internal rotation is of primary concern.

5.1 Introduction

As discussed in Chapter 3, the variability in radiographically measured acetabular orientation can result from mal-orientation of the pelvis during surgery. However, pelvic orientation during the acquisition of post-operative anterior-posterior pelvic radiographs has also been shown to impact the degree of acetabular orientations projected.¹⁹⁸

With respect to the radiographic reference frame, Murray¹⁶ defined radiographic inclination as the angle between the patient's longitudinal axis and the acetabular axis when projected onto the radiographic coronal plane and radiographic version as the angle between the acetabular axis and the radiographic coronal plane. As the acetabular component is fixed within the acetabulum of the pelvis, non-neutral pelvic orientation at the time of radiography will influence the position of the acetabular axis relative to the radiographic coronal plane (Figure 2.20). Therefore, the acetabular orientations as measured by Murray's¹⁶ definitions of radiographic orientation, are not solely a measure of the acetabular component position achieved intra-operatively, but are also a function of the pelvic deviation from neutral orientation during radiography.

With respect to radiographic pelvic orientation, pelvic posterior (-) / anterior (+) tilt and adduction (-) / abduction (+) are of primary concern (Figure 5.1). As pelvic radiographs tend to be taken in the supine position, pelvic external / internal rotation about its longitudinal axis is limited. The motion of pelvic adduction / abduction is coplanar with the radiographic coronal plane and can currently be estimated by fitting a line to the tear drops or base of the projected pelvis (Figure 1.13). However, pelvic posterior / anterior tilt is not coplanar with the radiographic coronal plane. This is further compounded by the fact that the degree of pelvic tilt varies between patients.²⁸

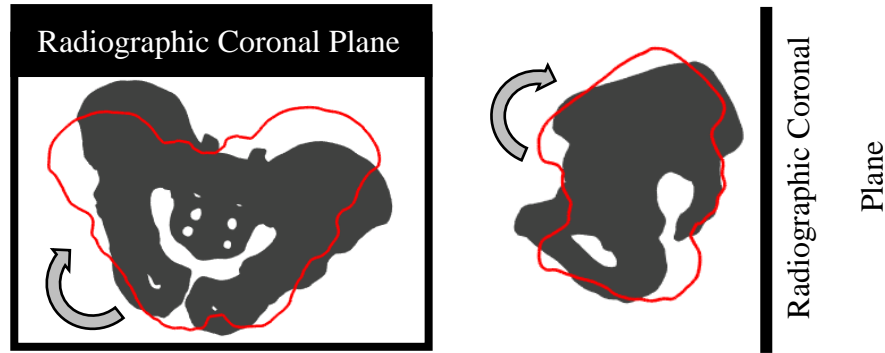


Figure 5.1 *Negative elemental pelvic rotations in the radiographic reference frame. Neutral pelvic outline depicted in red: a) Adduction c) Posterior tilt*

Pelvic tilt has been shown to impact the degree of radiographic version projected in 2D and, to a lesser degree, the radiographic inclination.¹⁹⁷ In order to establish a common reference frame of measurement between patients, pelvic tilt within each radiograph needs to be corrected by aligning the anterior pelvic plane with the radiographic coronal plane. Having neutralised the pelvis, the resulting orientation will be a factor of acetabular positioning alone.

The primary aim of this chapter was to develop a computational tool that could be used to reconstruct the 3D orientation of the pelvis and acetabular component relative to the radiographic coronal plane using a single low anterior-posterior pelvic radiograph (Objective 4). Following validation of this computational tool, the secondary aim of this chapter was to determine the impact of non-neutral pelvic radiographic positioning and magnification errors on the differences observed between the 2D radiographic and operative measures of acetabular orientation by applying the developed tool to a clinical cohort. The tertiary aim of this chapter was to evaluate the use of the transverse pelvic lines in THR surgery. From Chapter 4, the use of transverse pelvic lines was proposed to minimise intra-operative pelvic adduction / abduction and thus

radiographic variability in acetabular orientation. One possible method of assessing the use of the transverse pelvic lines was to employ them intra-operatively. Subsequently, radiographic outcomes for the transverse pelvic lines approach could be compared with standard practice.

5.2 Method

Two algorithms were developed within MATLAB (2016b, The MathWorks Inc., USA) for determining the 3D orientation of (i) the acetabular component and (ii) the pelvis relative to the radiographic coronal and sagittal planes using a single low anterior-posterior radiograph. In this instance, the radiographic sagittal plane is a plane that would be parallel to the sagittal view of a lateral radiograph of the hip. These algorithms were then applied to a clinical cohort ($n = 90$). This cohort comprised of three groups ($n = 30$). Each group consisted of equal numbers of males and females. All members of the study were operated on using the TAL approach by two orthopaedic surgeons at Musgrave Park Hospital.

To allow for adjustment of pelvic adduction, the head down tilt utility of the electronic operating table was employed intra-operatively. This allows an orthopaedic surgeon to control the height of the patients head relative to their feet. For the first group, the operating table was tilted head down (patients head was lowered whilst their feet were raised relative to the ground) by 7° (7° HD); the expected degree of pelvic adduction from previous research by the supervisory team. For the second group, the operating table was tilted head down by a patient-specific value as determined from transverse lines drawn on each patient's lower back (Y° HD, the table head down angle is adjusted until the TPL lines are approximately vertical via the use of a plumb line). The degree of table head down required was measured by placing a digital inclinometer on the rail

of the surgical table. For the final group, the table head down tilt was set to zero (0° HD). These groups were used to assess the ability of the transverse pelvic lines to reduce intra-operative pelvic adduction and thus the discrepancy between apparent operative and radiographic acetabular orientation.

With respect to the radiographic reference frame, pelvic neutrality was defined as the position of the pelvis when its anterior pelvic plane was parallel to the radiographic coronal plane and its sagittal pelvic plane was parallel to the radiographic sagittal plane or lateral view (Figure 5.2). In this instance, True inclination (*TI*) was thus defined as the angle between the acetabular axis and the radiographic sagittal plane when the pelvis was in a neutral radiographic orientation (Figure 5.2). True version (*TV*) was defined as the angle between the acetabular axis and the coronal plane when this is *projected* onto the radiographic sagittal plane, provided the pelvis was in a neutral radiographic orientation (Figure 5.2). Apparent measures of radiographic orientation are then measures of inclination (*ARI*) and version (*ARV*) relative to the radiographic coronal and sagittal views when the pelvis was in a non-neutral position (Figure 5.3).

5.2.1 Solver

A global solver (Particle Swarm Optimisation) was developed that predicted both 3D acetabular and pelvic orientation relative to measures of acetabular orientation and pelvic outlines within the post-operative radiographic reference frame. Two algorithms were contained within this solver for achieving this goal; one each for acetabular and pelvic orientation. The global solver was used to determine the optimal parameters for these algorithms simultaneously. The solver required a low anterior-posterior pelvic radiograph from which the outlines of the real projected acetabular cup face and pelvic had been obtained.

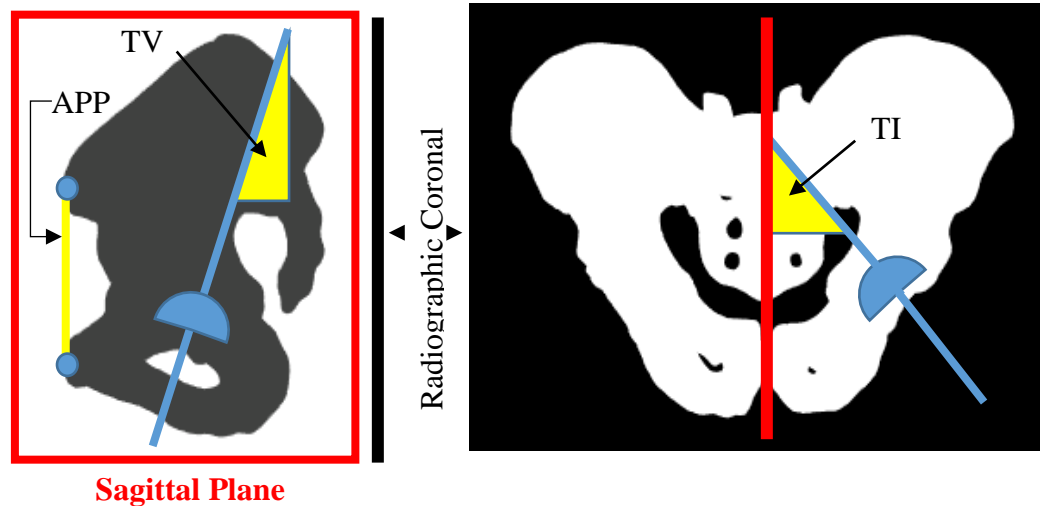


Figure 5.2 True version (TV) and inclination (TI), and neutral pelvic orientation in the radiographic reference frame. Anterior pelvic plane (APP) is parallel to the radiographic coronal plane and the pelvic sagittal plane is parallel to the radiographic sagittal plane.

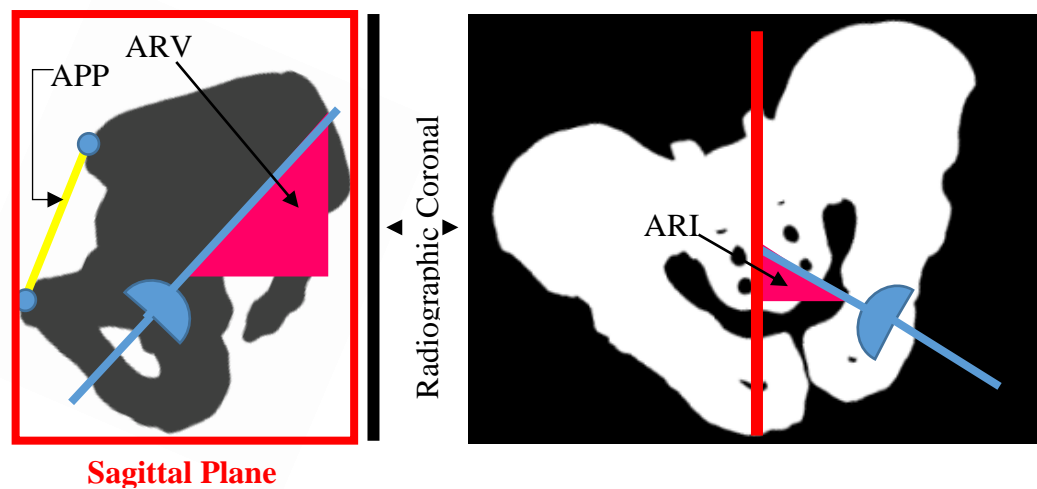


Figure 5.3 Apparent radiographic version (ARV), inclination (ARI), and non-neutral pelvic orientation in the radiographic reference frame.

5.2.1.1 3D Acetabular Orientation

A computational algorithm was developed to determine measures of 3D apparent radiographic acetabular orientation (ARI and ARV). The basic function of the

algorithm was to match a projected outline of a simulated acetabular component to that measured from a post-operative anterior-posterior pelvic radiograph through an iterative process. The true outline of the acetabular component was measured within MATLAB by selecting points along the perimeter of the acetabular component on the radiograph (Figure 5.4).

Within the solver, the simulated acetabular component was treated as a hemispheric point cloud with diameter equal to that of the acetabular component implanted in each patient. The acetabular point cloud (A_N) was initially orientated such that the centre of its face was coincident with the origin of a righthanded Cartesian coordinate frame. The face of the simulated acetabular point cloud was also initially arranged so that it was parallel to the transverse plane (x - z plane). Using the simulated values of ARI and ARV at each iteration, the simulated acetabular point cloud (A_R) was rotated relative to the coronal (x - y plane) and sagittal planes (y - z plane, Equation 1).

$$A_R = (R_x(-ARV)R_z(ARI)A_N) \quad (1)$$

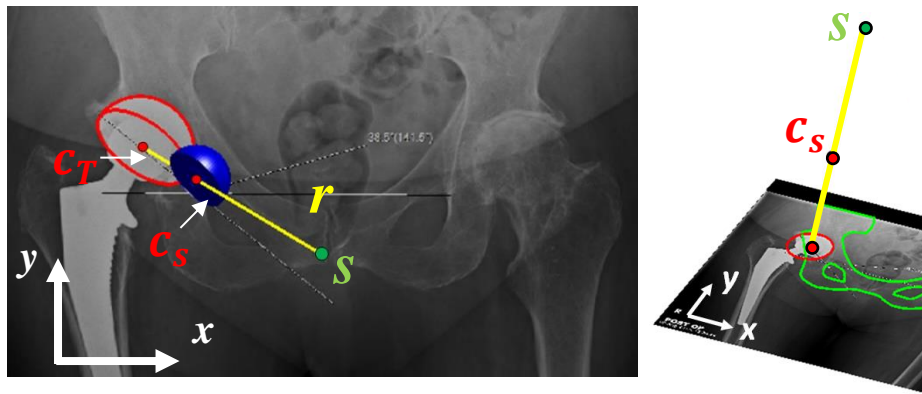


Figure 5.4 Reference frame used for determining apparent radiographic acetabular orientation.

Within the solver, the rotated acetabular point cloud was then allowed to move along a vector (\vec{r}) that connected the radiographic source (\vec{S}) to the centre of the true projected acetabular face (c_T , Equation 2, Figure 5.4). The rotated acetabular point cloud was allowed to move along this vector through the origin of its face (c_S). The distance moved along the vector by the acetabular point cloud was represented by a fraction (l) of the total path length of the vector (Equation 3). This fraction was generated as part of the iterative process of the solver. The centre of the true projected acetabular face (c_T) was obtained by determining the centroid of an ellipse that was automatically fitted to the real projected acetabular component face within MATLAB via image analysis techniques (Figure 5.4).

$$\vec{r} = \vec{c_T} - \vec{S} \quad (2)$$

$$\vec{c_S} = \vec{S} + l|\vec{r}| \quad (3)$$

Having positioned the simulated acetabular component within the radiographic reference frame, the simulated acetabular component was then projected onto the coronal radiographic plane via ray casting.²²⁴ At this stage, the outline of the simulated acetabular component projection was determined and its correspondence with the true acetabular component outline was established. Correspondence was obtained by re-interpolating the edge of the simulated acetabular component outline beginning with its most inferior point. The fitness of the solver was thus determined as the root mean square error of distances (d) between corresponding points on the true and simulated outlines (Equation 4).

$$f(l, ARI, ARV) = \sqrt{\frac{1}{n} \sum_{i=1}^n d_i^2} \quad (4)$$

Since the spatial location of the simulated acetabular component relative to the radiographic coronal plane is known, the solver enables differentiation between retroverted and anteverted components.

5.2.1.2 3D Pelvic Orientation

In the previous section, an algorithm was described for determining the 3D apparent radiographic orientation of the component relative to the radiographic coronal and sagittal planes. In order to establish a common reference frame of measurement between patients, the true orientation of the component was determined. To do this, the orientation of the pelvis relative to the radiographic coronal and sagittal views was established. An algorithm was developed that iteratively matched the projected mask of a simulated pelvis to the true pelvic shape from an anterior-posterior pelvic radiograph. To allow for shape variation between patients, statistical shape modelling was employed.

5.2.1.2.1 Statistical Shape Model Overview

Statistical shape models (SSMs) allow families of similar shapes to be represented by a single deformable model.²⁰⁸ They represent both the average shape of the family and the allowable variance within the family. In order to construct an SSM, a set of training shapes is required. Each training shape can be represented by a series of n points denoted by a vector x_i , where i represents the i^{th} shape of the training set (Equation 5).

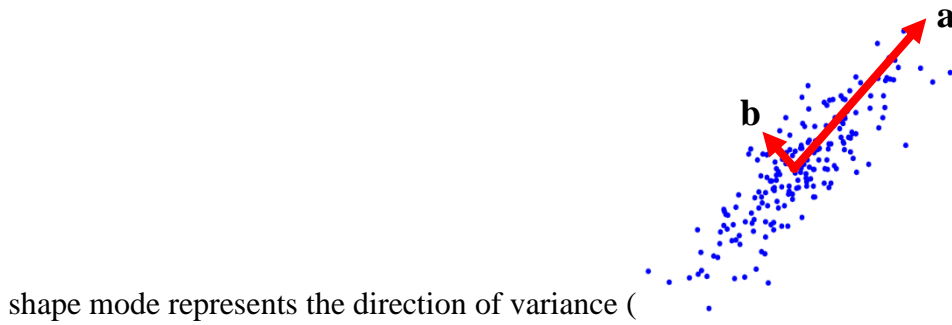
$$x_i = (x_{i0}, y_{i0}, z_{i0}, x_{i1}, y_{i1}, z_{i1}, \dots, x_{in}, y_{in}, z_{in})^T \quad (5)$$

To enable comparison, each of the n points must be sampled at corresponding landmarks across the training set. Additionally, to observe variance as a result of shape

alone, the training sets must be aligned. Having achieved this, the average shape (\bar{x}) can be obtained (Equation 6).

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (6)$$

Principal component analysis (PCA) can be used to statistically determine the variance relative to the average model. For each training example, the deviation between itself and the average shape is determined, and a covariance matrix can be obtained.²⁰⁸ Principal component analysis provides a series of principal components, or shape modes, denoted by the eigenvectors of the covariance matrix. Each eigenvector or



shape mode represents the direction of variance (Figure 5.5). These eigenvectors have corresponding eigenvalues that describe the magnitude of allowable variance in that direction.

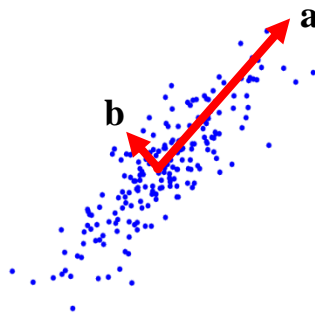


Figure 5.5 Example 2D data with two principal component axes: Principal component axis \vec{a} exhibits a greater magnitude of variance than \vec{b} .

Analysis of the eigenvalues allows identification of k principal components, or shape modes, that contribute to the majority of shape variance observed. Thus, a new shape can be obtained by applying a linear model where P^k is a matrix of the chosen eigenvectors ($3n \times k$) and b_i^k is a column vector containing k adjustment parameters (Equation 7). The adjustment parameters allow the data to be scaled along each of the chosen eigenvectors or shape modes. The magnitude of each adjustment parameter is selected such that it falls within three standard deviations of the allowable variance (λ_k) for that shape mode (Equation 8).

$$x_i = \bar{x} + \sum_k P^k b_i^k \quad (7)$$

$$-3\sqrt{\lambda_k} \leq b_i^k \leq 3\sqrt{\lambda_k} \quad (8)$$

5.2.1.2.2 Construction of Statistical Shape Models

Two gender-specific SSMs were created. The models were separated by gender as gender-specific differences could add to the overall observed variance between landmarks for a single SSM (Figure 5.6); i.e. allowable ranges for the shape adjustment parameters for a single SSM constructed from both genders may not be representative of either male or female pelvises.

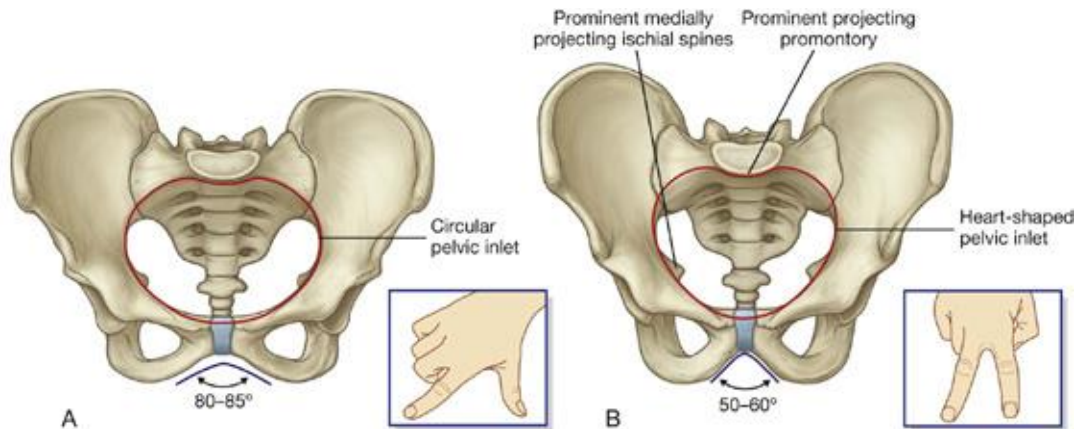


Figure 5.6 Gender specific differences between a) female and b) male pelvises²²⁵

In order to build a training set, available CT scans of pelvis (male = 29, female =17) were downloaded from the Virtual Skeleton Database.²²⁶ Initial manual segmentation was achieved via thresholding and by selecting unwanted regions within each CT scan using ImageJ²¹⁷ (Figure 5.7). With initial segmentation complete, surface models were created using the ImageJ 3DViewer plugin.²²⁷ The surface models tended to include defects and so were subsequently imported into MeshLab²²⁸ for cleaning. Within MeshLab the first stage of the cleaning process was to remove excess noise (e.g. the remaining parts of the femur or spine). In order to simplify the surface mesh, Poisson-disk sampling²²⁹ was used to re-sample points along its surface. Using the sampled points, surface reconstruction was achieved using ball pivoting.²³⁰ Remaining internal faces and holes were removed using the “Ambient Occlusion” and “Fill Hole” features within MeshLab. Although the sacrum has previously been shown to aid determination of pelvic tilt within the radiographic reference frame²⁰³, in this instance, the sacrum was removed from all pelvic models. This decision was made following the initial segmentation phase, in which the majority of CT scans demonstrated poor sacrum visibility. Inaccurate segmentation of the sacrum due to poor visibility would have resulted in a loss of precision.



Figure 5.7 Segmentation process: a) manual segmentation; b) mesh cleaning, simplification, and alignment; and c) final mesh.

The clean surface meshes were then imported into MATLAB for the formation of the two gender-specific SSMs. Within MATLAB, the first stage was to align all of the

pelves into a common reference frame. To achieve this, one pelvis from each gender was manually aligned through visual inspection. These two pelves were aligned such that their anterior pelvic planes were maintained parallel to the radiographic coronal plane and an axis connecting their ASISs was perfectly horizontal. This position is representative of that required for the definitions of true acetabular orientation. To align the remaining surface models, an implementation of the “Rigid Iterative Closest Point”²³¹ algorithm was employed within MATLAB.

Following alignment, the next step was to establish the correspondence between landmarks across all pelves for each gender model. Due to the complexity of pelvic geometry, non-rigid registration is required at this stage to ensure a clean correspondence. Non-rigid correspondence can be achieved by morphing a source surface mesh onto a target surface mesh (Figure 5.8). The source surface mesh was chosen randomly from the training set for each gender and morphed onto the remaining pelves for each set. Non-rigid registration was achieved using a “Coherent Point Drift”²³² algorithm within MATLAB. For the male SSM, the mean registration error was 2.23 mm (± 0.95 mm, 0 mm to 10.4 mm). For the female SSM, the mean registration error was 1.69 mm (± 0.46 mm, 0 mm to 9.35 mm). To understand these registration errors relative to the scale of the pelvis, they were compared to the average inter-ASIS distance (22.7 cm, distance between the anterior superior spines of the pelvis). These registration errors represent 0.98% (male) and 0.74% (female) of the average inter-ASIS distance indicating a high level of reconstruction accuracy. This indicates the use of realistic pelvi to build the statistical shape model. In turn, the statistical shape model is unlikely to produce pelvic models that are not within the pelvic family of shapes.

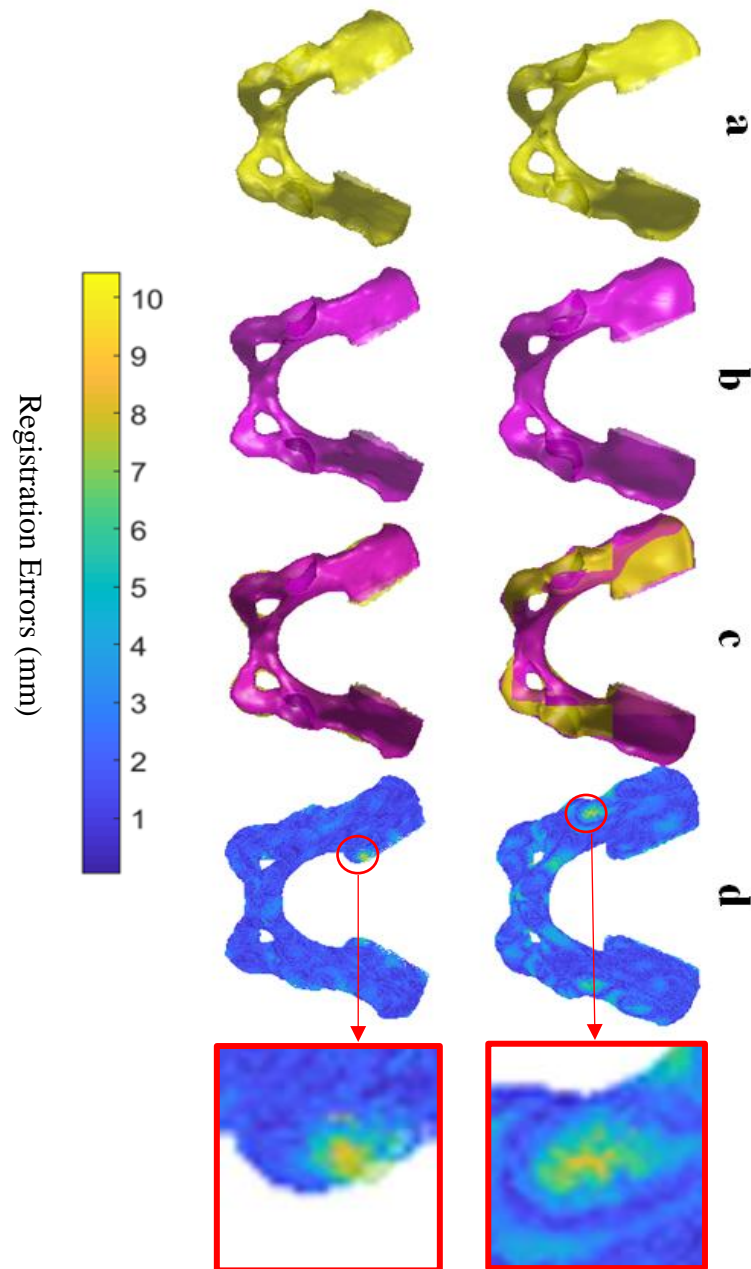


Figure 5.8 Registration errors during correspondence. Worst cases are presented for male (top row) and female (bottom row) cohorts: a) Source mesh b) Target mesh c) Registration achieved d) Registration errors in mm.

The shape models were then constructed within MATLAB (Figure 5.9). The number of shape modes for each model was selected by determining the number of shape

modes required to account for 96% of the observed variance. For the female SSM, the first six shape modes were selected and for the male model, the first nine modes were selected. The strongest shape modes for each SSM are displayed in Figure 5.10.

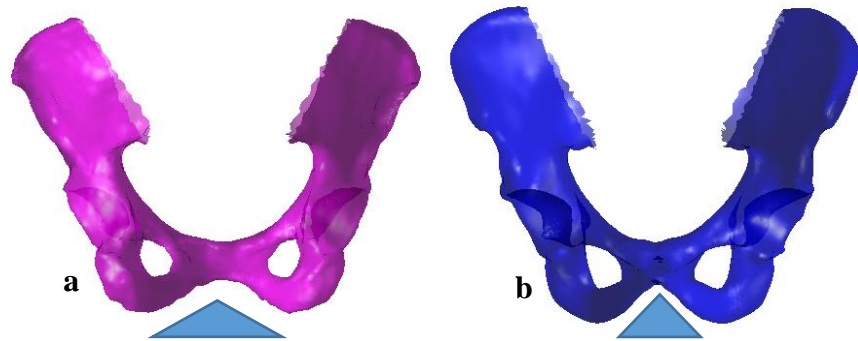


Figure 5.9 a) Female and b) Male mean SSMs of the pelvis. Male pubic arch angle is more acute than the female pubic arch angle.

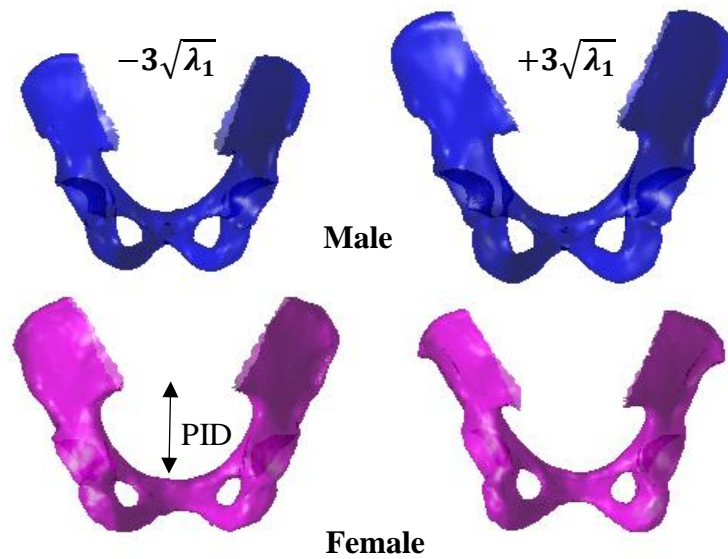


Figure 5.10 Strongest modes of variance for the male and female SSMs. Scale is the primary mode of variance for the male SSM whilst pelvic inlet depth (PID) was the primary mode of variance for the female SSM.

5.2.1.2.3 3D Radiographic Pelvic Orientation Reconstruction Algorithm

For each case, a gender-specific SSM was initially selected. Each iteration of the solver updated the shape parameters, orientation, and position of the shape model within the radiographic reference frame. Having achieved this, the pelvis was then projected onto the radiographic coronal plane (x - y plane) and a simulated pelvic image mask created. The solver seeks to maximise the correlation between the simulated pelvic mask and that obtained from the true radiograph. The true image mask was gained by manually selecting pelvic outlines from radiographs using MATLAB functions `impoly` and `poly2mask` (Figure 5.11).

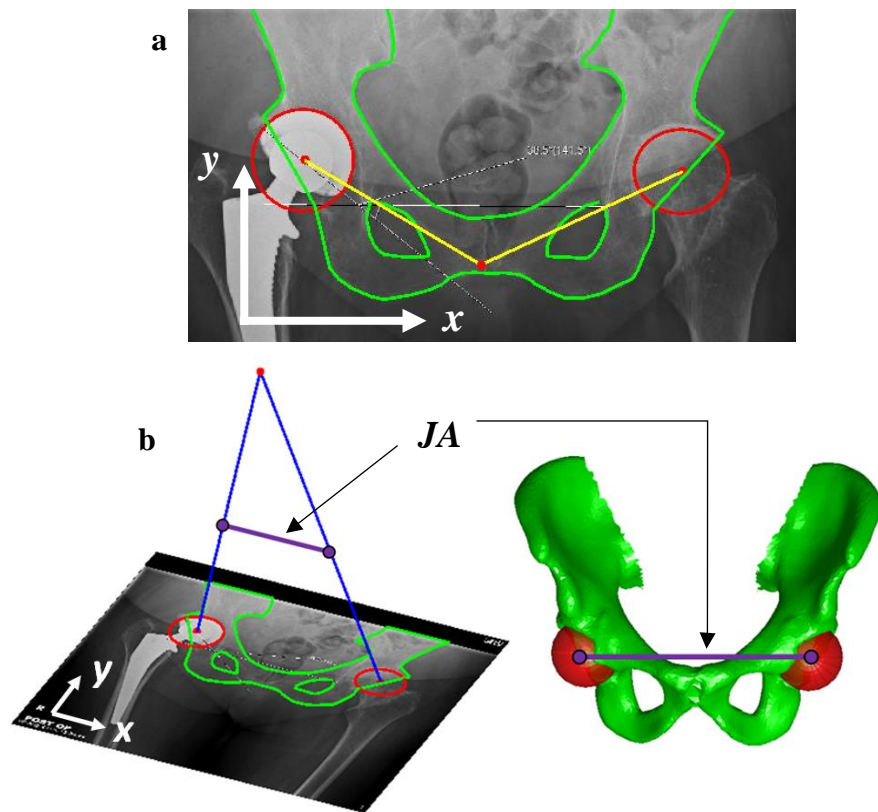


Figure 5.11 a) Landmarks selected for 3D pelvic reconstruction and b) fitting of the joint axis (JA) within the radiographic reference frame.

For each iteration, following an update of its shape parameters (Equation 7), the pelvic model was initially aligned such that the centre of its APP was coincident with the origin of a right-handed Cartesian coordinate system. The initial neutral orientation of the pelvic shape model (P_N) ensured that the pelvic APP was parallel to the radiographic coronal (x - y) plane and that its sagittal plane was parallel to the radiographic sagittal view (y - z plane). The pelvic model was then rotated (P_R) relative to the coronal and sagittal radiographic views (Equation 9). Within the radiographic reference frame, clockwise rotations about each axis were considered positive. Rotation about the z -axis or anterior-posterior axis was termed adduction (-) / abduction (+), whilst rotation about the x -axis or transverse axis was termed posterior (-) / anterior (+) tilt. In this position the location of the pelvic joint centres was determined via least squares fitting of spheres²³³ within each acetabulum. This enabled determination of an axis that connected the two hip joint centres, hereby called the joint axis (Figure 5.11).

$$P_R = (R_z(add)R_x(tilt)P_N) \quad (9)$$

Using the joint axis, the pelvis was then aligned between two rays that traced from the radiograph source to the true projected joint centres. This was achieved by determining the location at which the end points of the joint axis were most likely to coincide with each of the rays such that the pelvic mesh remained in front of the coronal plane. The true projected joint centres were obtained by fitting circles to the projected acetabular cup and femoral head on each radiograph (Figure 5.11). Following positioning of the pelvic model relative to the radiographic source, the facets of the pelvic model were projected onto the coronal view of the radiograph (x - y plane) via ray casting.¹⁹⁶ Due to the large number of facets within each pelvic SSM, image mask creation can be

slow due to the need to determine which of the many image pixels fall within each facet's projection. This portion of the algorithm was accelerated by exploiting barycentric coordinates, linear indices, and vectorisation within MATLAB. The degree of fit at each iteration was then established by determining the correlation between the simulated image mask and the true image mask (Figure 5.12). The `corr2` function within MATLAB was employed to achieve this.



Figure 5.12 Screenshot taken during binary image matching between the predicted image mask (green) and the simulated image mask (magenta).

5.2.1.3 Particle Swarm Optimisation

Due to the large number of variables, particle swarm optimisation (PSO) was used to determine the search direction between iterations in the aforementioned algorithm (Figure 5.13). Particle swarm optimisation, introduced by Kennedy et al in 1995,²¹⁰ is based on the concept of swarm intelligence. A swarm consists of many individuals where the overall behaviour or movement of the swarm is influenced by communication between its members. A PSO algorithm is initialised by randomly generating an initial population of search particles. In this instance, each search particle represents a combination of shape parameters and pelvic and acetabular orientations. For every iteration of the solver, the fitness value of each particle is assessed. In this

study, the fitness function seeks to determine the pelvic orientation and shape that maximises the correlation between the image mask and simulated image mask alongside the acetabular orientation that minimises the distance between the true and simulated projected cup face outlines. In each iteration, the search particles move through the search space. The velocity of each search particle is updated (Equation 10) via knowledge of their own personal best fitness (Pbest) and by the knowledge of the overall best fitness of the swarm (Gbest), where Pbest represents the fitness for a given particle and Gbest represents the best Pbest observed from a group of particles. The velocity vector (Equation 10) is used to update the position of the particles for the next iteration (Equation 11). When the position of the particles converge, PSO has found the optimum solution.

$$v_{i,n+1} = w_n v_{i,n} + c_1 r_{i,n} (Pbest_{i,n} - X_{i,n}) + c_2 R_{i,n} (Gbest_{i,n} - X_{i,n}) \quad (10)$$

$$X_{i,n+1} = X_{i,n} + v_{i,n+1} \quad (11)$$

The terms in equations 10 and 11 are defined below:

i	i^{th} individual
n	n^{th} iteration number
c_1	Acceleration coefficient (used to define the contribution or weighing of Pbest)
c_2	Acceleration coefficient (used to define the contribution or weighing of Gbest)
r	random constant ($0 < r < 1$)
R	random constant ($0 < R < 1$)
$Pbest$	personal best solution
$Gbest$	global best solution

X Position array
 V Velocity update array
 w inertia factor ($0 \leq w \leq 1$)

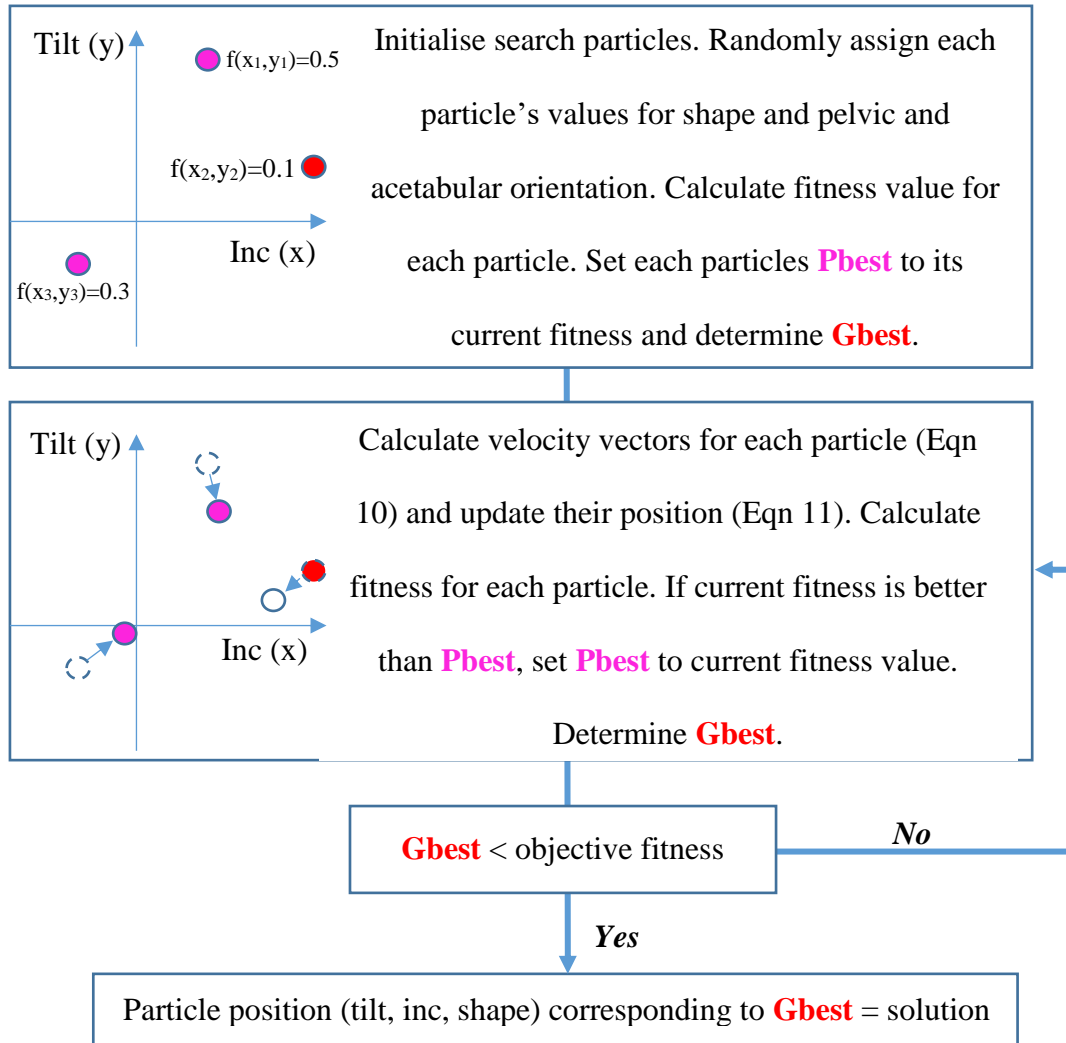


Figure 5.13 Flowchart for 2D example of particle swarm optimisation.

5.2.2 Analysis

Statistical analysis was conducted using the R programming language²¹⁸ and MATLAB (version 2016b, Math Works Inc., USA).

5.2.2.1 Verification

The primary aim of this chapter was to develop a computational tool that could be used to reconstruct the 3D orientation of the acetabular component and pelvis relative to the radiographic coronal plane using a single low anterior-posterior pelvic radiograph (Objective 4). Simulated radiographs²²⁴ were employed to test the technique for determining pelvic orientation from a single anterior-posterior radiograph (Figure 5.14). For each simulated radiograph ($n = 50$), the shape parameters, position, and orientation of the pelvic model were randomly selected. The source-to-detector distance in all cases was kept at 1 m (as per standard practice in Musgrave Park Hospital). Each simulated case was repeated three times. This was done to ensure that the solver delivered repeatable outcomes for a given simulated case. A lack of repeatability would potentially reflect the solvers failure to find global optima. A repeated measures ANOVA was applied to these measures to assess the repeatability of the solver. The ability of the solver to predict the simulated pelvic orientation was assessed using linear regression. Absolute errors were defined as the absolute difference between the simulated pelvic angle and that predicted by the solver.

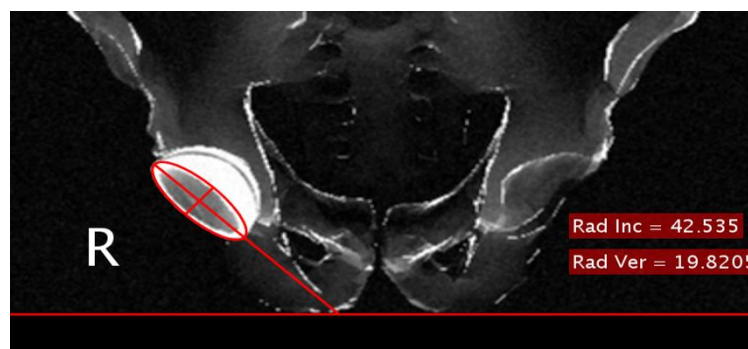


Figure 5.14 *Simulated radiographs were used to assess the validity of the solver.*

5.2.2.2 Clinical Cohort

The radiographic pelvic orientation solver was applied to a clinical cohort ($n = 90$). As previously described, this cohort comprised of three groups. For the first group, the operating table was tilted head down by 7° (7° HD). For the second group, the operating table was tilted down by a patient-specific value as determined from transverse lines (Chapter 4) drawn on each patient's lower back (Y° HD). For the final group, the table head down tilt was kept at zero degrees (0° HD, standard practice). Each group consisted of equal numbers of males and females. For both adduction / abduction and posterior / anterior tilt, linear regression models were fitted in which adduction / abduction or posterior / anterior tilt were treated as a function of gender, group and their possible interactions.

To obtain measures of apparent radiographic acetabular orientation (relative to the radiographic coronal and sagittal plane), the 3D radiographic cup orientation algorithm was individually applied to each case within the clinical cohort. The measures of apparent radiographic acetabular orientation were then converted to true measures of acetabular orientation (relative to the APP and pelvic sagittal plane) by reversing the acetabular component through the radiographic pelvic angles predicted in the previous step by the pelvic orientation solver. Measures of standard 2D radiographic acetabular orientation were determined by an orthopaedic surgeon using the method detailed in Figure 1.13. For each member of the clinical cohort, measures of apparent operative acetabular orientation (relative to the theatre floor and long axis of the theatre table) were obtained using the principles of stereo-photogrammetry by an orthopaedic surgeon at Musgrave Park Hospital.²³⁴

The secondary aim of this chapter was to determine the impact of non-neutral pelvic radiographic positioning and magnification errors on the differences observed between the 2D radiographic and operative measures of acetabular orientation by applying the developed tool to a clinical cohort. Having neutralised the pelvis with respect to the radiographic reference frame, differences between the true and the apparent operative acetabular orientation are solely the result of intra-operative pelvic positioning. The relative differences between the mean 2D radiographic, true and apparent operative acetabular orientations were used to assess the level of contribution of radiographic pelvic orientation and magnification errors to the observed differences between 2D radiographic and apparent operative measures of acetabular orientation.

The tertiary aim of this chapter was to evaluate the use of the transverse pelvic lines in THR surgery. To assess if there were any significant differences across the measures of inclination or version within each reference frame (2D radiographic, apparent radiographic, true, and apparent operative), a repeated measures ANOVA was applied. For both the true inclination and version, general linear regression models were fitted in which the cup angle was treated as a function of gender, group (7° HD, Y° HD – transverse pelvic lines, 0° HD – standard practice) and their possible interactions. For all models (linear regression and repeated measures ANOVA), Tukey post-hoc analysis was used.

5.3 Results

5.3.1 Verification

The primary aim of this chapter was to develop a computational tool that could be used to reconstruct the 3D orientation of the acetabular component and pelvis relative to the radiographic coronal plane using a single low anterior-posterior pelvic radiograph

(Objective 4). Strong correlations were observed between the applied rotations (randomly selected) and the predictions of the rotation solver for both pelvic adduction / abduction ($r^2=0.99$) and anterior/ posterior tilt ($r^2=0.92$); Figure 5.15. The mean absolute error between the applied and predicted values for pelvic adduction / abduction was 0.86° ($\pm 0.77^\circ$, 0.01° to 3.07°). For pelvic anterior / posterior tilt, mean absolute error was 2.95° ($\pm 1.98^\circ$, 0.01° to 7.05°). No significant differences were observed between applied and predicted measures of posterior / anterior tilt ($p=0.77$) and adduction / abduction ($p=0.53$) across the three repetitions. These tests demonstrated that the solver could theoretically provide accurate, repeatable measures for posterior / anterior tilt and adduction / abduction relative to the coronal and sagittal views from simulated radiographs. The average run time for the solver was 213 seconds (SD 53s, 125s to 297s).

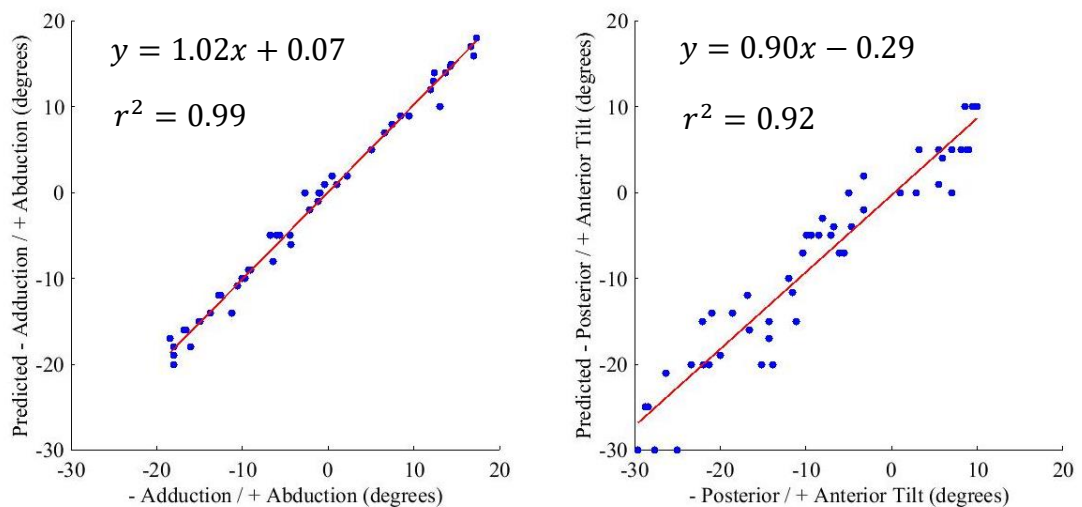


Figure 5.15 Strong correlations were observed between true and predicted values for adduction / abduction and posterior / anterior tilt.

5.3.2 Clinical Cohort

5.3.2.1 3D Radiographic Pelvic Orientation

Overall, the mean posterior (-) / anterior (+) tilt predicted by the solver for the full clinical cohort described earlier, i.e. when treating the three groups (0° HD, 7° HD, and Y° HD) as a single cohort, was 9.75° ($\pm 6.08^\circ$, -4.51 to 23.7°). For pelvic adduction (-) / abduction (+), the mean angle obtained was -0.88° ($\pm 4.07^\circ$, -9.67° to 8.58°). Thus, posterior / anterior tilt exhibited greater variability than adduction / abduction relative to the radiographic reference frame (Figure 5.16).

After fitting a general linear regression model, neither group ($p=0.33$) nor gender ($p=0.92$) were found to be significantly correlated with radiographic pelvic adduction / abduction. Similarly, group was not significantly correlated with radiographic posterior / anterior tilt ($p=0.32$). However, gender was found to be significantly correlated with radiographic posterior / anterior pelvic tilt ($p<0.001$). The mean posterior (-) / anterior (+) tilt for males was 7.11° ($\pm 6.11^\circ$, -4.51° to 23.5°). For females, the mean posterior (-) / anterior (+) tilt was 12.3° ($\pm 4.85^\circ$, -0.59° to 23.7°). Thus, females tended to be more anteriorly tilted than males in the supine radiographic position.

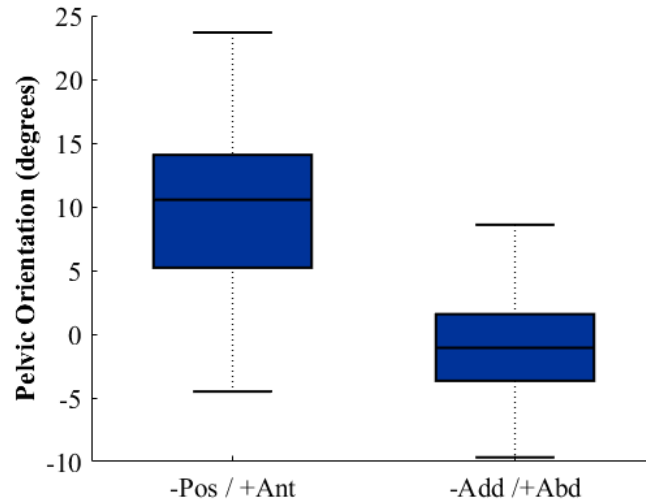


Figure 5.16 *Posterior (Pos) / Anterior (Ant) tilt exhibited greater variability than Adduction (Add) / abduction (Abd) relative to the radiographic reference frame.*

Pelves tended to be anteriorly titled in the supine radiographic position.

5.3.2.2 3D Radiographic Acetabular Orientation

True inclination (i.e. relative to the pelvic sagittal plane, TI, Figure 5.2), exhibited lower variability (Table 5.1, Figure 5.17) than 2D radiographic inclination (i.e. as measured in conventional radiographs, RI). Conversely, true version (i.e. relative to the anterior pelvic plane, TV, Figure 5.2), exhibited greater variability than 2D radiographic version (Table 5.1, RV, Figure 5.18). With respect to measures of inclination, significant differences were observed between the types of measurement ($p < 0.001$). Apparent operative inclination (AOI), i.e. relative to the operating theatre floor (Figure 3.1), was found to be significantly different from all other measures of inclination ($p < 0.001$). Only measures of RI (Figure 1.13) and TI (i.e. relative to the anterior pelvic plane, Figure 5.2) were found to be statistically similar ($p = 0.87$).

Having neutralised the pelvis with respect to the radiographic reference frame, differences between the true inclination (TI) and the target AOI are solely the result of intra-operative pelvic positioning. The mean absolute difference observed between

AOI and TI was 7.0°. As the mean magnitude of TI is higher than AOI, it can be assumed that the pelvis tends to be adducted and / or internally rotated intra-operatively (Figure 3.8).

Table 5.1 *Measures of inclination and version with respect to different reference frames.*

	Inclination (degrees)				Version (degrees)			
	RI	ARI	TI	AOI	RV	ARV	TV	AOV
Mean	42.2	39.4	40.2	33.2	23.2	30.7	40.3	44.7
SD	5.8	1.95	3.90	2.63	5.00	5.05	7.41	6.73
Min	24.2	36.6	31.0	24.7	11.3	23.4	20.5	29.5
Max	54.6	44.9	48.0	40.4	34.5	37.1	55.6	59.5

With respect to measures of version, significant differences were observed between all reference frames ($p < 0.001$, Figure 5.18). For measures of true version (TV), neither group nor gender were found to be significant predictors. However, although statistical significance was not reached for gender, there was evidence of a potential trend ($p = 0.07$): true version was found to be higher for females ($\bar{x} = 41.7^\circ \pm 6.56^\circ$, 29.3° to 53.8°) compared to males ($\bar{x} = 38.7^\circ \pm 8.00^\circ$, 20.5° to 55.6°). In this instance, AOV was found to be higher than TV by a mean angle of 4.40° . The results suggest that the pelvis is more posteriorly tilted during surgery than it is during the post-operative radiograph (Figure 3.9).

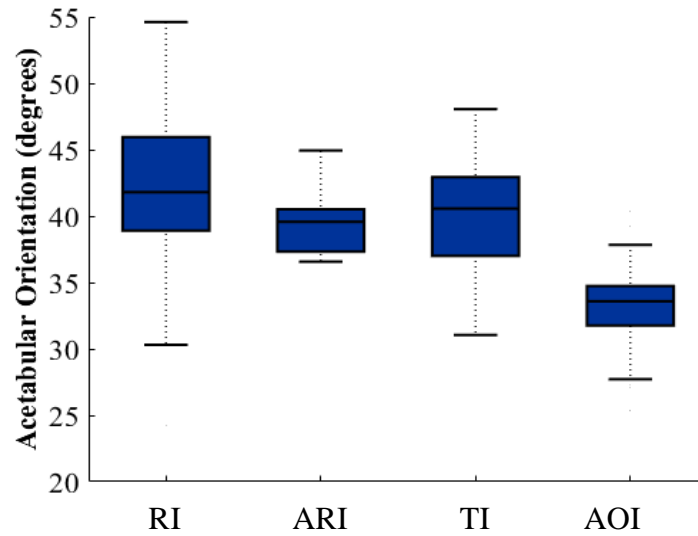


Figure 5.17 Measures of inclination with respect to different reference frames.

Values of TI tend to be approximately 7° higher than measures of AOI.

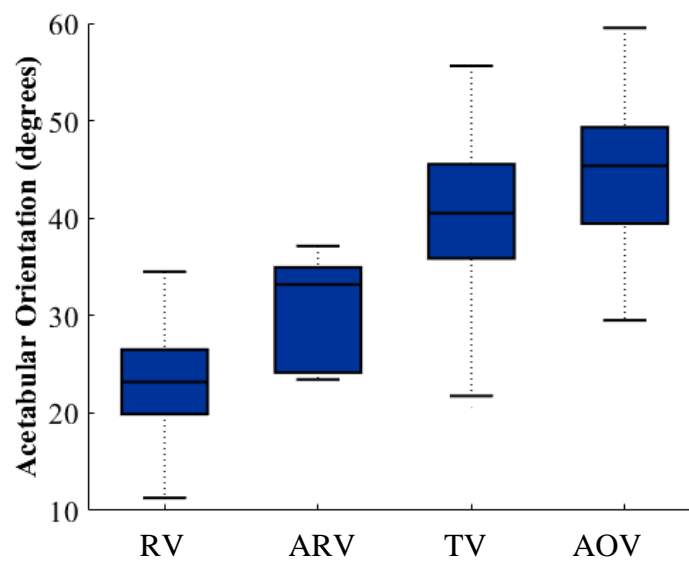


Figure 5.18 Measures of version with respect to different reference frames. Values of

TV tend to be approximately 4.40° lower than measures of AOV.

5.3.3 Non-neutral Pelvic Positioning During Radiography

The secondary aim of this chapter was to determine the impact of non-neutral pelvic radiographic positioning and magnification errors on the differences observed between

the 2D radiographic and operative measures of acetabular orientation. By analysing the differences in means between the 2D radiographic, the true, and AOV reference frames, it can be seen that radiographic pelvic positioning and magnification errors accounted for approximately 79.5% $(TV - RV / AOV - RV)$ of the observed differences between the 2D radiographic and AOV reference frames. For inclination, only 22.2% $(TI - RI / AOI - RI)$ of the observed differences between the 2D radiographic and AOV reference frames were accounted for by radiographic pelvic positioning and magnification errors.

5.3.4 Utility of Transverse Pelvic Lines

The tertiary aim of this chapter was to evaluate the use of the transverse pelvic lines in THR surgery. When using the transverse pelvic lines, the mean degree of pelvic adduction observed was 4.26° (SD 2.07°, 0.00° to 7.70°). For measures of true inclination, group (0°HD –standard practice, Y°HD – transverse lines, 7°HD) alone was found to be a significantly correlated with true inclination ($p < 0.001$, Table 5.2, Figure 5.19). For group, the only significant contrast observed was between the 7° HD group and the 0° HD group ($p < 0.001$). The use of the transverse pelvic lines did not significantly alter the mean TI achieved when compared to normal practice.

Table 5.2 Measures of true inclination for each group. The Y° HD group corresponds to those patients whose table orientation was set by ensuring the transverse pelvic lines were oriented vertically with respect to the theatre floor.

	0° HD	Y° HD	7° HD
Mean	41.5°	39.8°	38.3°
SD	3.54°	4.15°	4.40°
Min	34.8°	31.2°	27.7°
Max	48.0°	47.9°	47.1°

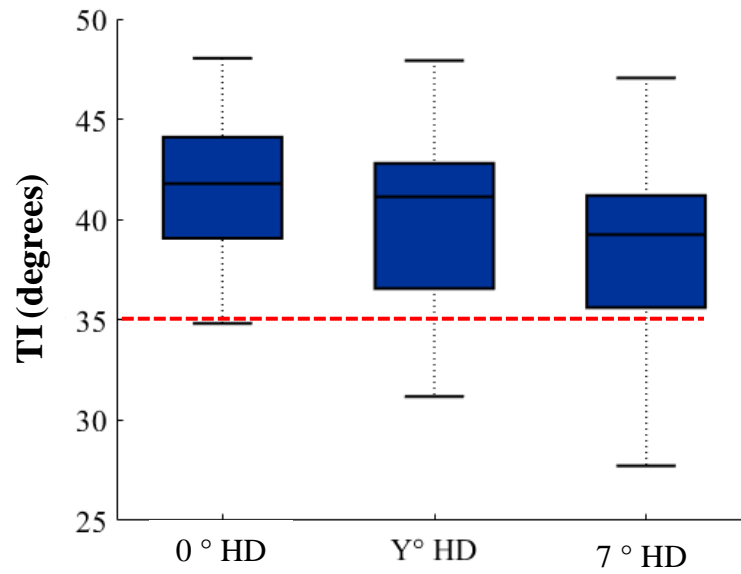


Figure 5.19 Significant differences were observed between the 7° HD and 0° HD groups for measures of true radiographic inclination (TI).

5.3.5 Impact of Table Orientation on Safe Placement

With respect to this study, an acetabular component was classified as safe if its true 3D inclination was within 10° of its target intra-operative orientation of 35°. The percentage of acetabular components placed safely by group are shown in Table 5.3.

Table 5.3 Percentage of acetabular components placed safely by group (0° HD, Y° HD or 7° HD).

Group	Safe
0° HD	83.3% (n=25/30)
Y° HD	96.7% (n=29/30)
7° HD	96.7% (n=29/30)

5.4 Discussion

The primary aim of the research presented within this chapter was to develop a computational tool that could be used to reconstruct the 3D orientation of the acetabular component and pelvis relative to the radiographic coronal plane using a single low anterior-posterior pelvic radiograph. The developed computational tool successfully predicted both adduction / abduction and posterior / anterior tilt of the pelvis in a verification test ($r^2 = 0.99$ and $r^2 = 0.92$ respectively; Figure 5.15) with higher mean accuracy for pelvic adduction / abduction ($0.86 \pm 0.77^\circ$ [0.01–3.07°] vs. $2.95 \pm 1.98^\circ$ [0.01–7.05°] for pelvic tilt). The secondary aim of this research was to determine the impact of non-neutral pelvic radiographic positioning and magnification errors (the difference between true and 2D radiographic acetabular orientation) on the differences observed between the 2D radiographic and operative measures of acetabular orientation. These factors contributed to approximately 79.5 % (version) and 22.2% (inclination) of the observed differences between the 2D radiographic and apparent operative acetabular orientations. The tertiary aim of this chapter was to evaluate the use of the transverse pelvic lines in THR surgery. Although no significant differences in true inclination were observed between the 0° and Y° HD groups, fewer cases were outside the defined safe zone when using the transverse pelvic lines (Table 5.3).

Overall, the mean radiographic posterior (-) / anterior (+) tilt observed was 9.75° ($\pm 6.08^\circ$, -4.51 to 23.7° , Figure 5.16). For radiographic pelvic adduction (-) / abduction (+), the mean angle obtained was -0.88° ($\pm 4.07^\circ$, -9.67° to 8.58°). These radiographic pelvic orientations had the impact of reducing the variability in true inclination (TI, 17°) when compared to standard 2D measures of radiographic inclination (RI, 30.4°). Conversely, they significantly increased the variability for true version (TV, 35.1°)

when compared to standard 2D measures of radiographic version (RV, 23.2°). A limitation of this study is that it does not provide a measure for radiographic pelvic external / internal rotation. However, the influence of pelvic external / internal rotation is limited in the supine position.

A limitation of this study is that there were no ground-truth CT scans to validate the measures obtained. However, the measures of supine pelvic tilt ($\bar{x} = 10.9^\circ \pm 7.6^\circ$, -7° to 27°) obtained by Babisch et al²³⁵ via the use of post-operative CT scans reflect the measures obtained in this study ($\bar{x} = 9.75^\circ \pm 6.08^\circ$, -4.51° to 23.7°). Thus, the tool developed for predicting radiographic pelvic orientation produces values that are within range of pre-existing clinical measurements.

Within this study it was observed that the pelvis tends to be anteriorly tilted in the supine position. This finding is supported by the literature.^{28,68,195,235} In an experimental study conducted by Haenle et al¹⁹⁷ using a Sawbones[®] pelvis, it was observed that 2D radiographic version decreased with increasing pelvic anterior tilt. Subsequently, as observed in this study (Figure 5.18), reversing the degree of anterior tilt increases the angle of true version when compared to their 2D counterparts. Due to the substantial variation in pelvic tilt (-4.51° to 23.7°) between patients in the supine position, there is a low correlation between standard 2D measures of radiographic version and true version ($r = 0.13$). Consequently, no linear mathematical relationship exists between the two factors. This is supported by the findings of Marx et al¹⁹⁸ who also observed low correlation between their 2D radiographic versions and their true versions obtained from CT scans ($r = 0.15$).

In order to reduce errors in 2D radiographic version, Lewinnek et al¹¹⁵ attempted to align their cohort's anterior pelvic planes (APP) such that they were parallel to the

radiographic coronal plane. Although this may be advantageous for reducing errors in 2D radiographic version, it may contribute to increased errors in 2D radiographic inclination. During radiography, as observed by this research, the pelvis tends to be anteriorly tilted. Reversing the degree of anterior tilt to align the APP with the radiographic coronal plane has the impact of increasing 2D radiographic version. As the degree of 2D radiographic version increases, the accuracy of the 2D measure of radiographic inclination decreases. This can be illustrated using the simulated radiographic model previously described in Chapter 3 (Figure 5.20). It is therefore not advantageous to correct for pelvic tilt during patient positioning for a 2D radiograph. This highlights the need for 3D reconstruction (as employed in this research) over the use of traditional 2D measures.

Previously within the literature, pelvic tilt has been reported to have a minimal impact on 2D radiographic inclination.^{197,237} In an experimental study conducted by Haenle et al¹⁹⁷ using a Sawbone® pelvis, a low average discrepancy of 2° was observed between true and 2D radiographic inclination. This is supported by the simulated radiographic model in which an average discrepancy of 1.6° was obtained under conditions equivalent to those employed by Haenle et al¹⁹⁷. However, the maximum true version investigated by Haenle et al¹⁹⁷ was only 20°. In practice, the use of the TAL approach may result in higher true versions than those investigated by Haenle et al¹⁹⁷ and consequently higher deviations between true and 2D radiographic inclination (Figure 5.20).

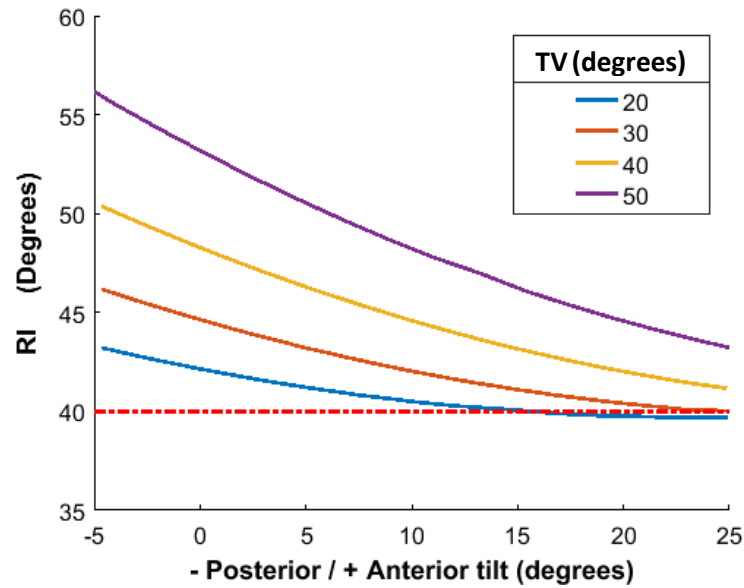


Figure 5.20 Anterior pelvic tilt reduces the discrepancy between true (TI - red dash line) and 2D (RI) radiographic inclination. The discrepancy is amplified by higher magnitudes of true version (TV).

In this study, it was observed that the mean of true version was approximately 4.40° degrees lower in the post-operative supine position when compared to measures of AOV taken in the *lateral decubitus* position. This is within the differences observed by Kanazawa et al¹⁹⁵ (3.1°) and by Hayakawa et al²³⁶ (5.1°). This suggests that the pelvis is more posteriorly tilted in the operative lateral position than it is in the post-operative supine position. Consequently, orthopaedic surgeons can typically expect their true versions to be less than the AOV they observe in surgery.

Despite lack of significant differences in true inclination between the 0° and Y° HD groups, a higher number of cases were placed safely when using the transverse pelvic lines (Table 5.3). Thus, the number of outlying cases was reduced when using the transverse pelvic lines. These findings are similar to findings for CAOS in current practice, which have found that while CAOS has not improved average acetabular

orientation¹⁸⁴⁻¹⁸⁷ achieved, it can reduce the variability^{183-184,187}. Thus, the transverse pelvic lines may be considered as a cost-effective alternative to reducing variability.

Despite exhibiting a weaker relationship with true inclination in chapter 3 (Table 3.1), it is possible that internal pelvic rotation may play a greater clinical role than pelvic adduction in introducing acetabular component orientation errors. For example, correcting for patient-specific pelvic adduction had no significant impact (i.e. no significant differences in mean true inclination between the 0° (standard practice) and Y° HD (transverse pelvic lines) groups), which implies the degree of intra-operative pelvic adduction is minimal. However, significant differences were observed between the 0° and 7° HD groups. Increasing the head down angle of the theatre table forces the pelvis to abduct. As expected, the pelvises in the 7° HD group were found to be more abducted than their 0°HD counterparts by a mean difference of 7.07° (intra-operative measures from transverse pelvic lines). From Chapter 3, a linear trend between pelvic adduction (-) / abduction (+) and true inclination was observed (Table 3.1, $TI = -0.93(Add) + 34.7$) so an approximate mean change of 7° may have been expected between the 0° and 7° HD groups for measures of true inclination. However, as seen in Table 5.2, the mean difference observed was only 3.2°. One reason for this lower estimate is that it is suspected that the pelvises investigated tended to be internally rotated intra-operatively during acetabular impaction. This is supported within the available literature.^{27,195} Internal rotation (Figure 3.8) counteracts pelvic abduction, which reduces the differences observed between the 0° and 7° HD groups for measures of true inclination. However, pelvic internal rotation, if left unchecked, has the impact of increasing true inclination (Figure 3.8). To reduce the discrepancy between apparent operative and true measures of inclination, an increase in the head down angle of the theatre table may be an affordable and practical clinical option.

The current average run time for the solver was 213 seconds. However, this excludes the time taken for the outlines of the pelvis and acetabular cup to be manually extracted from the post-operative radiograph. Manual segmentation of the radiograph is a tedious task and is thus likely to prevent clinical adoption. To enable clinical application, future work may be done with respect to automatic radiographic segmentation.

Within this study, a computational tool was created that could determine the true orientation of the acetabular component relative to the pelvis from a single low AP pelvic radiograph. This tool has the potential to provide orthopaedic surgeons with more accurate knowledge of the 3D acetabular orientation achieved without the use of multiple radiographic views or CT scans. Thus, the use of this tool can help to reduce the amount of radiation required per patient whilst increasing the accuracy of existing acetabular measures relative to a single anterior-posterior pelvic radiograph. This has the potential to highlight mal-orientated hip implants that would otherwise be considered as safe whilst using traditional 2D radiographic measures. Future work with respect to this approach may involve simplification of the computation model. If an intra-operative measure of true version can be obtained, it may be used to determine the degree of true version (relative to the radiographic reference frame) and pelvic tilt without the second stage (statistical shape modelling) of the current computational model. One possible approach for obtaining true version intra-operatively is to add a pubic symphysis reference arm to patient supports during THR alongside the use of a digital compass (Figure 5.21). At this stage of development, the solver used optimised parameters for acetabular cup and pelvic orientation simultaneously. Future work may also investigate the merits of optimising these parameters independently e.g. solving for acetabular followed by pelvic orientation.

5.5 Conclusion

A computational tool was developed and used to identify the impact of radiographic pelvic mal-rotation and magnification errors on the differences observed between apparent operative and true acetabular component orientation. Most of the variation observed between apparent operative and true version (79%) was accounted for by radiographic pelvic mal-rotation and magnification errors. Conversely, a small fraction (22%) of the variation between apparent operative and true inclination was accounted for by these factors. The remaining difference is a result of intra-operative pelvic positioning. In particular, operative pelvic internal rotation is of concern. Clinically, operative pelvic internal rotation plays an important role in increasing the observed differences between apparent operative and true inclination. Operative pelvic internal rotation may be minimised by using the coronal alignment guide described in Chapter 4 or by alternating the head down angle of the theatre table. Alternatively, a new target apparent operative inclination may be employed.

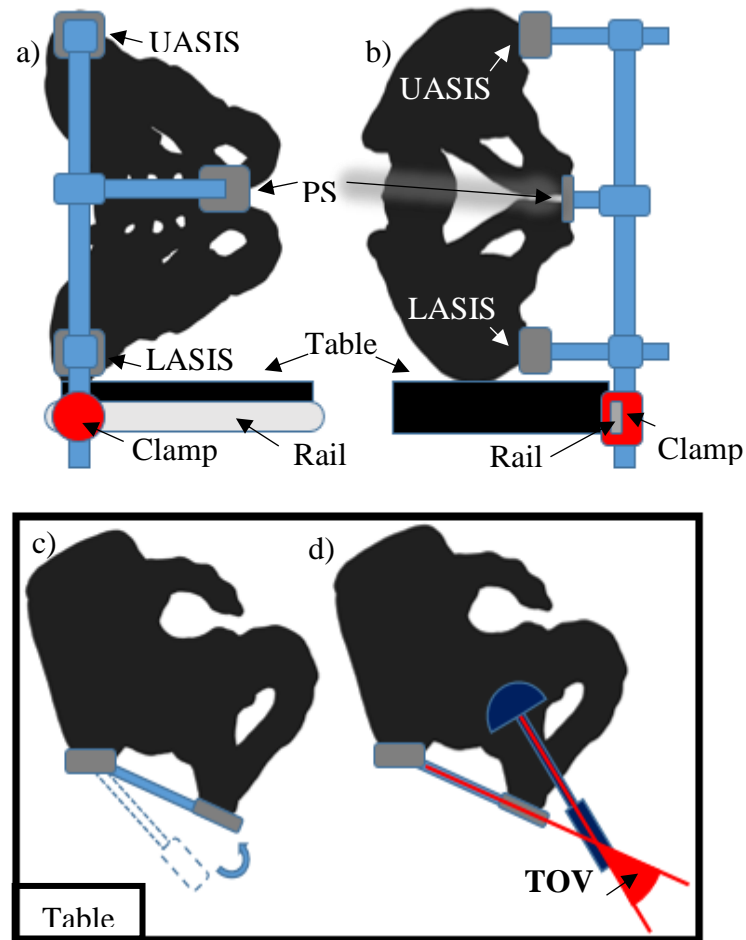


Figure 5.21 New patient supports for measuring true version (TV) intra-operatively. Upper (U) and lower (L) anterior superior iliac spine (ASIS) supports are used to maintain the sagittal pelvic plane parallel to the theatre table. A rotational pubic symphysis (PS) reference arm is used to indicate the anterior pelvic plane (APP). a) Coronal view b) Transverse view c and d) Sagittal view with rotational PS reference arm and the measure of TV.



SIX

Acetabular Component Orientation due to Intra-operative Pelvic Orientation

Overview: In Chapter 5, it was shown that errors in acetabular orientation could be reduced by adjusting the head down angle of the theatre table. Alternatively, orthopaedic surgeons may choose to aim for a different apparent operative inclination. To choose an appropriate new target angle for apparent operative inclination, knowledge of likely intra-operative pelvic orientations is required. A new computational tool was created that could predict measures of intra-operative pelvic orientation using a combination of apparent operative acetabular orientation and post-operative acetabular orientation measured from radiographs. This tool was validated using stereo-photogrammetry of a physical model of the pelvis and then applied to a clinical cohort to estimate the likely intra-operative pelvic orientation of each patient. On average, it was observed that the pelvis tended to be internally rotated, adducted, and posteriorly tilted during THR. When using a TAL approach, only pelvic external / internal rotation contributed significantly to the variance in true inclination. Findings suggest that, to counteract operative pelvic mal-rotations, an orthopaedic surgeon should typically aim for an apparent operative inclination that is 9° less than their target true inclination.

6.1 Introduction

Currently, variability exists between an orthopaedic surgeon's intra-operative assessment of apparent acetabular orientation and the 2D radiographic acetabular orientation observed post-operatively.²⁹⁻³¹ As highlighted in the previous chapter, when using the TAL method, radiographic pelvic orientation and magnification errors can account for approximately 22% and 80% of the differences observed between 2D radiographic and apparent operative measures of inclination and version respectively. The remaining differences between true measures and apparent operative measures are a function of intra-operative pelvic positioning.

When using a mechanical alignment guide (MAG) approach, apparent operative acetabular orientation may be approximated by the fixed angles of the guide as determined by the manufacturer. The accuracy of this estimate is subject to the level of surgical skill with the technique. However, through an experimental study, Grammatopoulos et al¹⁷¹ demonstrated that orthopaedic surgeons could achieve a high degree of accuracy with respect to their target apparent operative acetabular orientations. In their study, orthopaedic surgeons, on average, could achieve their desired apparent operative inclination and version to within 3° and 1°. Thus, in this instance, the fixed angles of the alignment guide may be used as an appropriate estimate for apparent operative acetabular orientation.

With respect to the TAL approach, the use of digital inclinometers aligned with the handle of the introducer may be used to provide an accurate estimate of apparent operative inclination (AOI) intra-operatively. However, this does not provide a solution for apparent operative version (AOV). Due to the variation in native TAL version,¹¹⁸ accurate estimations of apparent operative version are currently not readily

available without the use of more complex theatre set-ups. For example, precise measures of AOV and AOI may be gained via the use of stereo-photogrammetry.²⁷ Stereo-photogrammetry uses at least two cameras to capture and reconstruct points relative to a calibration jig of known dimensions²³⁴ — in this instance, the apparent orientation of the introducer handle relative to the theatre.

Given measures of apparent operative acetabular orientation, true orientation (Chapter 5) and pelvic adduction / abduction (Chapter 5), the primary aim of this chapter was to determine the intra-operative pelvic orientation that accounted for the remaining discrepancy between true and apparent *operative* acetabular orientation. Due to the nature of the solution space, it is not possible to determine the pelvic orientation required for this transformation without using known angles for at least one of the pelvic axes. As pelvic adduction / abduction tends to exhibit the least variability, it was chosen as the controlled measure of pelvic orientation.

As discussed in Chapter 3, a limitation of the theoretical model is that it could not identify which pairings and/or magnitudes of elemental pelvic rotations would be likely to occur together in practice. Thus, the secondary aim of this study, was to identify the primary modes of intra-operative pelvic orientation that influence the resultant variation in radiographic acetabular orientation in clinical practice i.e. determine the likely pairs of pelvic orientation that would occur in practice. As discussed in Chapter 5, altering the head down angle of the theatre table or an appropriate choice of target apparent operative inclination may be used to counteract operative pelvic mal-positioning. The tertiary aim was then to use the findings from this study to identify the target intra-operative acetabular orientations required to counteract the impact of intra-operative pelvic orientation.

6.2 Method

A mathematical solver was created within MATLAB® (2015b, The MathWorks Inc., USA) that predicted measures of intra-operative pelvic orientation based on measures of true acetabular orientation (relative to the radiographic frame), apparent operative acetabular orientation and pelvic adduction / abduction. Initial validation of the solver was obtained via an experimental stereo-photographic set up. Following validation, the solver was applied to a clinical cohort (Chapter 5, 0° HD, n = 30). Using the values predicted for intra-operative pelvic orientation, limits for combined pelvic orientations were then identified. A pelvic mal-rotation was classified as safe if its corresponding true inclination fell within 10° of its target. Details of the above methods are provided in the following sub-sections.

6.2.1 Reference Frames and Rotations

As with Chapter 3, rotation of the pelvis in the operative *lateral decubitus* position about its longitudinal axis (Cartesian x-axis) was regarded as internal (+) / external (−) rotation. Rotation of the pelvis about its anterior-posterior axis (Cartesian z-axis) was regarded as abduction (+) / adduction (−). Rotation of the pelvis about its transverse axis (Cartesian y-axis) was termed anterior (+) / and posterior (−) pelvic tilt (Figure 6.1).

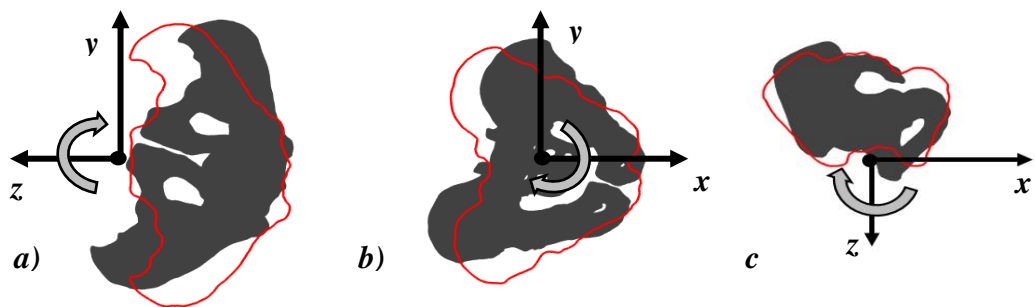


Figure 6.1 Negative elemental pelvic rotations for a left operative hip (neutral pelvic outline depicted in red): a) External rotation b) Adduction c) Posterior tilt.

6.2.2 Algorithm for MATLAB

The solution for rotation and tilt is found by minimising the distance between a predicted acetabular vector and a true one (a vector orientated with respect to the known apparent operative orientation). Ideally, an orthopaedic surgeon should orientate the acetabular component about the hip joint centre of rotation ($\hat{\mathbf{c}}_N$) of a neutral pelvis (pelvic sagittal plane parallel to the floor). However, in practice, the pelvis tends to be mal-rotated intra-operatively. Consequently, the acetabular component is inserted relative to the rotated joint centre of rotation. As with Chapter 3, the mal-rotated operative position of the hip joint centre-of-rotation ($\hat{\mathbf{c}}_R$) relative to its neutral position ($\hat{\mathbf{c}}_N$) was found using Equation 1.

$$\hat{\mathbf{c}}_R = \mathbf{R}_z(add)\mathbf{R}_x(rot)\mathbf{R}_y(tilt)\hat{\mathbf{c}}_N \quad (1)$$

The introducer axis ($\hat{\mathbf{i}}$) can be represented by a line that would be coincident with the handle of the introducer intra-operatively. Initially, the introducer, or acetabular, axis was treated as a unit vector collinear with the x -axis ($\hat{\mathbf{e}}_1$). Angles for apparent operative inclination (AOI) and version (AOV) can be used to determine the operative location of the acetabular cup axis ($\hat{\mathbf{i}}_o$, Equation 2).

$$\hat{\mathbf{i}}_o = \mathbf{R}_y(-AOV)\mathbf{R}_z(AOI)\hat{\mathbf{e}}_1 + \hat{\mathbf{c}}_R \quad (2)$$

In practice, once impacted, the position of the acetabular axis remains fixed relative to the pelvis. The location of the true acetabular axis ($\hat{\mathbf{i}}_{TS}$) for each simulated pelvic orientation can be found by reversing the operative position of the pelvis (Equation 3).

$$\hat{\mathbf{i}}_{TS} = \mathbf{R}_y(-tilt)\mathbf{R}_x(-rot)\mathbf{R}_z(-add)\hat{\mathbf{i}}_o \quad (3)$$

Angles for true inclination (TI) and version (TV, using the approach from Chapter 5) can be used to represent the actual location of the true acetabular axis ($\hat{\mathbf{i}}_T$) achieved by the orthopaedic surgeon relative to the neutral pelvis (Equation 4).

$$\hat{\mathbf{i}}_T = (\mathbf{R}_y(-TV)\mathbf{R}_z(TI)\hat{\mathbf{e}}_1) + \hat{\mathbf{c}}_N \quad (4)$$

If the pelvic orientation used to simulate the true introducer axis ($\hat{\mathbf{i}}_{TS}$) is correct, then the simulated ($\hat{\mathbf{i}}_{TS}$) and true acetabular axis ($\hat{\mathbf{i}}_T$) will be aligned. Measures of pelvic internal / external rotation and posterior / anterior tilt are thus determined by minimising the angular separation between the simulated and true acetabular axes. A function (Equation 5) to calculate the alignment between the true and simulated introducer axes can then be defined as:

$$f(rot, add, tilt) = \cos^{-1}(\hat{\mathbf{i}}_{TS} \cdot \hat{\mathbf{i}}_T) \quad (5)$$

Due to the nature of the solution space (a single optimum in a trough within the search space, Figure 6.2), Equation 5 was evaluated using the `fmincon` function within MATLAB (a gradient-based algorithm).

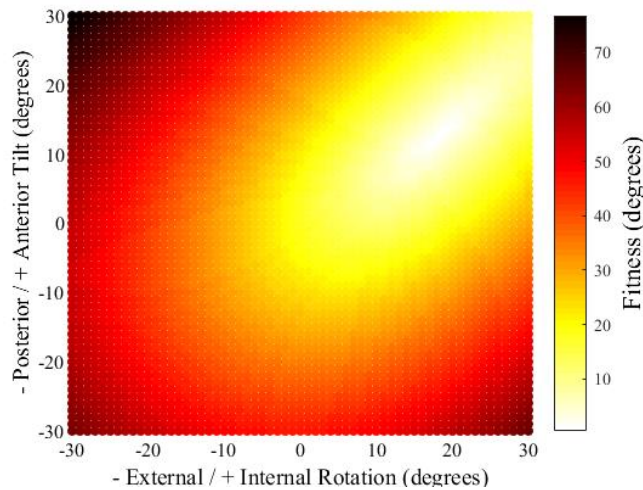


Figure 6.2 *Example solution space of solver for a given set of input parameters (AOI, AOV, TI, TV and pelvic adduction).*

6.2.3 Validation

An experimental set up was performed in which a Sawbones[®] pelvis (Sawbones, Pacific Research Laboratories Inc., USA) was attached to a jig that allowed rotation of the Sawbones[®] pelvis about each of its three axes. The acetabular component was represented by a 3D printed hemisphere that was implanted at a fixed version within the acetabulum. The hemisphere contained a lever arm mechanism that allowed for adjustment of the apparent operative inclination of the acetabular component. Thus pelvic rotation was controlled by the base of the jig and inclination was controlled by the cup lever arm. Accurate reconstruction of the pelvic and lever arm orientations was achieved using stereo photogrammetry (SP). This enabled the resultant true acetabular orientation to be determined for a range of known pelvic orientations which is not clinically achievable without the acquisition of expensive CAOS. Reconstruction using SP requires the location of each camera (Logitech Webcam Pro 9000 HD, Logitech, Romanel-sur-Morges, Switzerland) relative to their image frame to be determined. This can be achieved by using a calibration frame with known 3D coordinates (Figure 6.4). Additional 3D coordinates can then be reconstructed by using their relative location to the calibration frame within each image frame. In this instance a calibration frame with 12 markers was used (Figure 6.4).

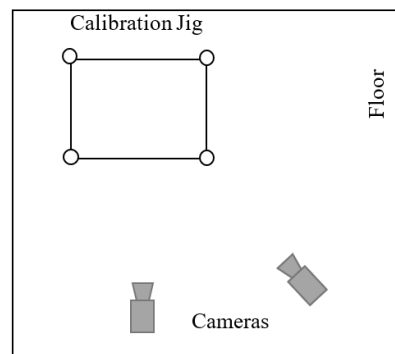


Figure 6.3 *Birds eye view of experimental set up*

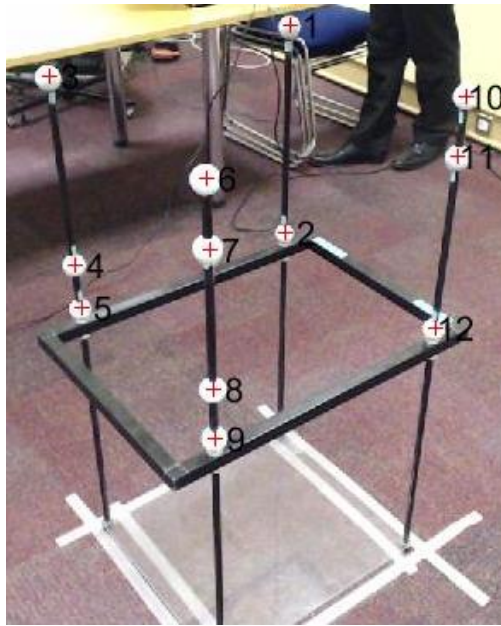


Figure 6.4 Calibration frame for stereo-photographic calibration

To allow stereo reconstruction for each set-up ($n = 48$), four images were captured ($n=192$). The first pair of stereo images captured the pelvic and lever arm orientations when the pelvis had been mal-rotated (Figure 6.5a and Figure 6.5b). This was to simulate intra-operative mal-positioning of the pelvis and the resultant apparent operative orientation of the acetabular component. The second pair captured the pelvic and lever arm orientation when the pelvis had been returned to its radiographic position (anterior pelvic plane parallel to the radiographic coronal plane, Figure 6.5c and Figure 6.5d). This was to simulate the neutral position of the pelvis alongside the resultant true orientation of the acetabular component. Pelvic orientation was identified using two common pelvic landmarks in each set of stereo images ($n = 4$): the anterior superior iliac spines and pubic tubercles. To enable more accurate and repeatable identification of common pelvic landmarks across a pair of stereo images, polystyrene spheres were attached to the pelvis (Figure 6.5). The introducer axis, or lever arm, was identified within each stereo image by fitting a line to it.

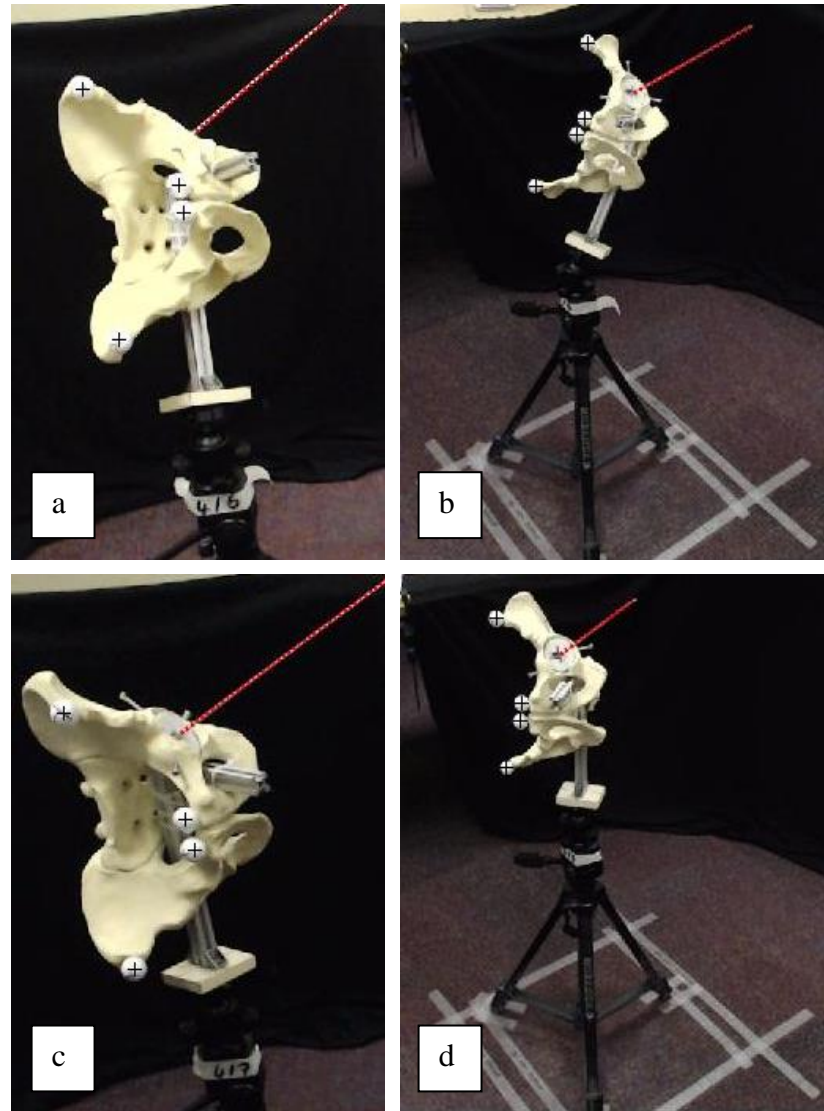


Figure 6.5 a) & b) Stereo pair of images of mal-rotated pelvis, c & d) Stereo pair of images of pelvis returned to its radiographic position. The acetabular axis was identified within each stereo image by fitting a line to it. Pelvic anterior superior iliac spines and pubic tubercles were used as pelvic landmarks.

To assess the accuracy of measured inclination reconstructed using SP, a digital inclinometer was used at each instance of the study to record the angle of inclination actually achieved. Overall, there was a strong correlation ($r = 0.98$, $p < 0.01$, $n = 96$, between measures of inclination measured in-situ and those reconstructed. A low mean absolute reconstruction error of 0.68° ($\pm 0.42^\circ$, 0.00° to 1.72° , $n = 96$) was also

calculated. Therefore, the SP procedure was able to accurately reconstruct 3D angles. Overall, strong significant correlations were also observed between the measures of stereo pelvic external / internal rotation ($r = 0.88$, $p < 0.001$, $n = 48$) and posterior / anterior tilt ($r = 0.90$, $p < 0.001$, $n = 48$), and those predicted by the solver (Table 6.1). The max error in both cases was associated with an extreme pelvic orientation that resulted in the view of the pelvic markers becoming obstructed. As such, it is believed that these errors are a result of registration errors rather than the solver.

Table 6.1 *Summary of validation outcomes*

	Ext / Int	Post / Ant
R	0.88 ($p < 0.001$)	0.90 ($p < 0.001$)
Mean Error	2.15°	2.56°
Sd Error	2.40°	1.31°
Min Error	0.00°	0.00°
Max Error	10.9°	4.54°

6.2.4 Analysis

The primary aim of this chapter was to determine the intra-operative pelvic orientation that accounted for the remaining discrepancy between true and apparent operative acetabular orientation. Measures of pelvic adduction / abduction from the 0° HD group ($n=30$) alongside their corresponding apparent operative and true measures of acetabular orientation (Chapter 5) were used as input variables for the solver. The 0° HD group was used as this group best represented normal surgical practice (no alterations made to the theatre table). Use of the solver enabled measures of external / internal rotation and posterior / anterior tilt of the pelvis to be determined.

The secondary aim of this chapter was to identify the primary modes of intra-operative pelvic orientation that clinically influence the resultant variation in radiographic acetabular orientation. To identify which modes of pelvic orientation significantly contributed to changes in true inclination, multiple linear regression was applied using the `lm` function within the R statistical computing language.²¹⁸ Pelvic external / internal rotation, adduction / abduction and posterior / anterior tilt were treated as the independent variables. To investigate the effect of different surgical variables (surgeon, gender, hip side, and BMI), general linear models were fitted to measures of external / internal rotation, adduction / abduction and posterior / anterior tilt.

As discussed in Chapter 5, altering the head down angle of the theatre table or an appropriate choice of target apparent operative inclination may be used to counteract operative pelvic mal-positioning. The tertiary aim was thus to find the target intra-operative acetabular orientations required to counteract the impact of intra-operative pelvic orientation (Objective 5). Using the pelvic intra-operative orientations predicted by the solver alongside measures of intra-operative pelvic adduction (0° HD, Chapter 5), the target apparent operative inclinations that an orthopaedic surgeon would have had to achieve to get a range of true inclination post-operatively was determined within MATLAB (2016b, The MathWorks Inc., USA). True inclination was evaluated at 5° intervals within the Lewinnek safe zone.¹¹⁵ Target apparent operative versions were not evaluated because this is subject to the native TAL version for this cohort.

The limits of allowable pelvic mal-orientation were determined by analysing the pelvic rotations from the cohort that resulted in the true acetabular inclinations being within 10° of their respective apparent operative inclinations. As apparent operative measures of inclination were accurately determined in this study using stereo-photogrammetry,

a lower threshold of 5° was also analysed. This lower threshold was to allow for errors in surgical estimation of apparent operative inclination if stereo-photogrammetry had not been used intra-operatively.

6.3 Results

The primary aim of this chapter was to determine the intra-operative pelvic orientation that accounted for the remaining discrepancy between true and apparent operative acetabular orientation. On average, the pelves investigated were found to be internally rotated, adducted and posteriorly tilted during THR (Table 6.2, Figure 6.6). Of note, pelvic posterior / anterior tilt exhibited the greatest magnitude of variability.

The secondary aim of this chapter was to identify the primary modes of intra-operative pelvic orientation that clinically influence the resultant variation in radiographic acetabular orientation. To understand the clinical impact of combined pelvic rotations, a general linear model ($r^2=0.62$, $p < 0.01$) was fit to measures of true inclination in which pelvic external / internal rotation, adduction / abduction, and posterior / anterior tilt during surgery were treated as independent effects. Only pelvic external / internal rotation contributed significantly to the variance in true inclination (Table 6.3). General linear models did not find significant effects for pelvic external / internal rotation ($r^2=0.14$, $p = 0.42$), adduction / abduction ($r^2=0.25$, $p = 0.13$), and posterior / anterior tilt ($r^2=0.20$, $p = 0.24$) as a function of surgeon, BMI, gender or hip side.

Table 6.2 *Measures of intra-operative pelvic orientation (SD = standard deviation).*

	- Ext / + Int	- Add/ + Abd	- Post / + Ant
Mean	8.96°	-4.26°	-1.62°
SD	7.00°	2.07°	10.2°
Min	-6.90°	-7.70°	-21.7°
Max	23.9°	0.00°	21.8°

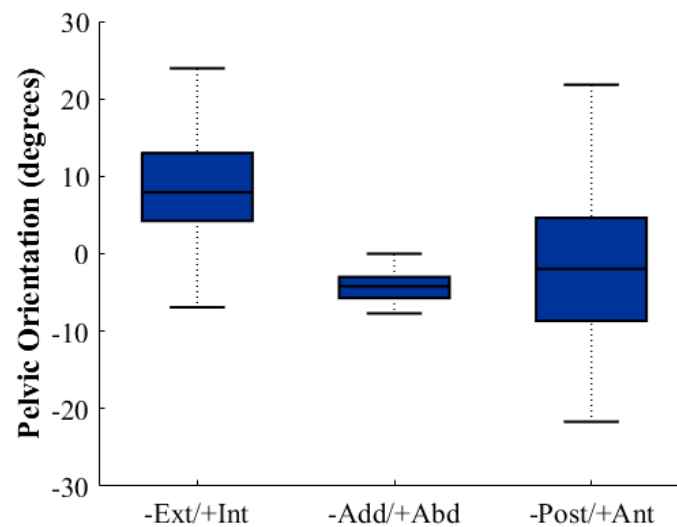


Figure 6.6 Pelvic orientations observed during THR

Table 6.3 Investigating the impact of combined pelvic rotations on true inclination via multiple regression analysis.

	Estimate	SD Error	<i>T</i> -value	<i>P</i>
(Intercept)	36.3	1.38	26.4	0.00
Ext / Int	0.44	0.07	6.01	0.00
Add/ Abd	-0.29	0.22	-1.35	0.20
Post / Ant	-0.5	0.05	-1.04	0.31

The tertiary aim of this chapter was to find the target intra-operative acetabular orientations required to counteract the impact of intra-operative pelvic orientation. Using the estimates of pelvic intra-operative orientations achieved, the target apparent operative inclinations that an orthopaedic surgeon would have had to achieve to get their desired true inclination post-operatively was determined (Table 6.4). Overall, it was predicted that surgeons should typically aim for an apparent operative inclination that is 9° less than their desired true inclination. However, considerable variability

exists in the target apparent operative inclination due to intra-operative pelvic positioning (Figure 6.7).

Table 6.4 *Range of target apparent operative inclinations (AOI) required to obtain true inclination (TI) within the Lewinnek safe zone ($40^{\circ} \pm 10^{\circ}$). Orthopaedic surgeons should typically aim for an AOI that is 9° less than their intended TI.*

TI	30°	35°	40°	45°	50°
Mean	21.1°	26.0°	31.0°	35.9°	40.8°
SD	4.18°	4.22°	4.26°	4.31°	4.37°
Min	11.9°	16.7°	21.5°	26.2°	30.9°
Max	29.6°	34.5°	39.4°	44.3°	49.1°

With respect to allowable pelvic deviation, when using the TAL approach, the pelvis is allowed to significantly deviate about its medio-lateral axis (posterior / anterior tilt). However, both pelvic external / internal rotation and adduction / abduction are limited (Table 6.5).

Table 6.5 *Allowable pelvic deviations from neutral to get within 10° and 5° of a given target true inclination.*

Target	Boundaries	-External /+Internal	-Adduction /+Abduction	-Posterior /+Anterior
10°	LB	-6.90	-7.70	-14.7
	UB	10.8	0.00	18.6
5°	LB	-6.90	-7.70	-12.7
	UB	5.59	-2.00	5.53

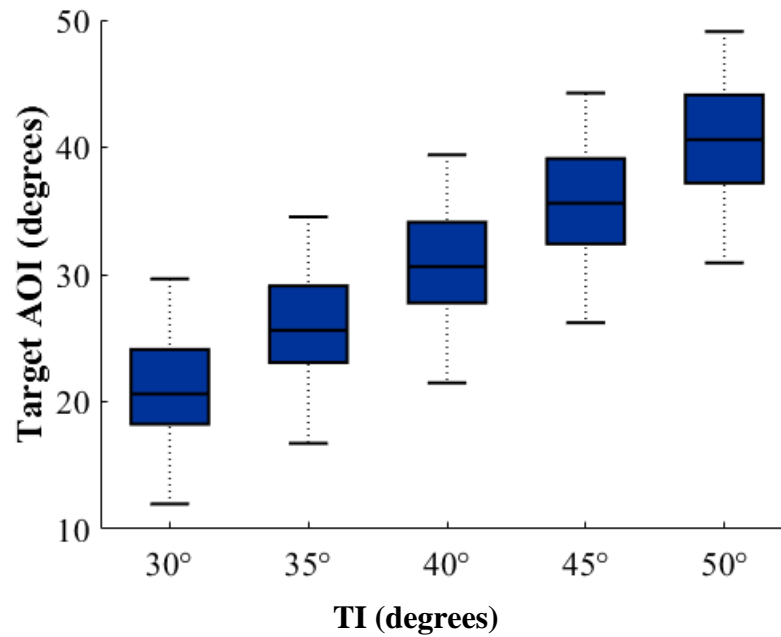


Figure 6.7 Wide variability in target apparent operative inclinations (AOI) were needed to compensate for intra-operative pelvis orientation in order to obtain target true inclination.

6.4 Discussion

The primary aim in this chapter was to determine the intra-operative pelvic orientation that accounted for the remaining discrepancy between true and apparent operative acetabular orientation. On average, it was observed that the pelvis tended to be internally rotated, adducted, and posteriorly tilted during THR. The secondary aim of this chapter, having identified likely intra-operative pelvic mal-rotations, was to identify the primary modes of intra-operative pelvic orientation that clinically influence the resultant variation in radiographic acetabular orientation (Objective 5). Unlike Chapter 3, which identified pelvic adduction / abduction as a key theoretical concern, only pelvic external / internal rotation contributed significantly to the variance in true inclination for the clinical cohort studied here (Table 6.3). The tertiary aim of this chapter was to find the target intra-operative acetabular orientations

required to counteract the impact of intra-operative pelvic orientation. Based on the operative pelvic mal-rotations identified for this study's clinical cohort, an orthopaedic surgeon should aim for an operative inclination that is 9° less than their target true inclination.

6.4.1 Intra-operative Pelvic Orientation

Within this study, it was observed that, on average, the pelvis tended to be internally rotated, adducted, and posteriorly tilted during THR when using the TAL approach. This is in agreement with the available literature.^{27,195} However, the magnitude and range of pelvic orientation deviated from some previously reported values. The measures of pelvic posterior / anterior tilt ($-1.62^\circ \pm 10.2^\circ$), pelvic adduction / abduction ($-4.26^\circ \pm 2.07^\circ$) and external / internal rotation ($8.96^\circ \pm 7.00^\circ$) observed in this study are within range of those observed by Grammatopoulos et al²⁷ pre-operatively during patient positioning (posterior / anterior tilt, $-8^\circ \pm 16$, adduction / abduction $-4^\circ \pm 6$, external / internal rotation $8^\circ \pm 7^\circ$). However, for both external / internal rotation and adduction / abduction they exceed the ranges reported by Kanazawa et al¹⁹⁵ (external / internal rotation $3^\circ \pm 4.8^\circ$, adduction / abduction $-0.5^\circ \pm 3.3$, posterior / anterior tilt, $-2.1^\circ \pm 6^\circ$). Differences between the values observed in literature and those obtained in this study may result from different surgical practices and/or the use of different patient supports.²⁷

A limitation of the theoretical model presented in Chapter 3 was its inability to identify the pairings and/or magnitudes of elemental pelvic rotations that would likely occur together in practice. In theory, pelvic adduction should be the strongest contributor to changes in the observed apparent and true inclinations. However, pelvic adduction / abduction tended to be low and the more variable pelvic external / internal rotation

(Figure 6.6) was the strongest predictor for changes in the observed apparent and true inclinations (Table 6.3). Excessive rotation of the pelvis about its longitudinal axis ($<11^\circ$, Table 6.5) should therefore be avoided. Although not used within this study, the new coronal alignment tool presented in Chapter 4 could be used to minimise pelvic internal / external rotation during patient positioning.

6.4.2 Target Apparent Operative Inclination

A limitation of the TAL approach is that it does not provide a means for controlling apparent operative inclination. When using the TAL approach, apparent operative inclination is still controlled using external landmarks, such as the theatre floor (as a substitute for the patient's pelvic sagittal plane). Traditionally, orthopaedic surgeons have aimed for 45° of apparent operative inclination relative to the theatre floor in order to get a 2D radiographic inclination of 45° . However, as illustrated by this study, orthopaedic surgeons should typically aim for an apparent operative inclination that is 6.8° less than their target radiographic inclination ($TI=AOI-9^\circ$, RI is typically 2.2° lower than TI, Chapter 5, Table 5.1). In practice, if an orthopaedic surgeon wants to obtain 45° of true inclination, they should aim for 36° of apparent operative inclination.

Achieving a target true inclination of 45° is subject to an orthopaedic surgeon's ability to achieve an apparent operative inclination of 36° . With respect to current practice, the most popular choices for controlling apparent operative inclination are the freehand approach and a mechanical alignment guide (Appendix A). With respect to the freehand approach, low accuracies have been illustrated with as little as 26% ($n = 27/105$)^{169,170} of cases being reported as being placed within 10° of their target 2D radiographic orientation. Improved accuracy using a mechanical alignment guide for controlling apparent operative inclination has been demonstrated. In a clinical study conducted by Hassan et al¹⁷², 84% ($n = 42/50$) of their cases were placed within 10°

of their target 2D radiographic orientation when using a mechanical alignment guide. However, inaccuracies remain. In an experimental study conducted by Grammatopoulos et al¹⁷¹ using a Sawbones[®] pelvis, it was observed that on average, orthopaedic surgeons typically underestimate their apparent operative inclination by -3° ($\pm 5^{\circ}$, -21 to 4°) when using a mechanical alignment guide. Consequently, it may be inferred that, due to surgical inaccuracy, orthopaedic surgeons should aim for 39° of apparent operative inclination. Alternatively, they may attach a digital inclinometer to the handle of the introducer (which is the practice of this study's supervisory orthopaedic surgeon) to ensure an exact apparent operative inclination of 36° .

6.4.3 Limitations

A limitation of the model is that it requires knowledge of the apparent intra-operative orientations of the acetabular component achieved. As discussed in the introduction of this chapter, this can be estimated if a MAG is being used. However, due to the variation in TAL version, more complex theatre set-ups are required for determining the apparent operative version. In this instance, the principles of stereo-photogrammetry were applied. However, this is not an applicable approach for routine practice. As discussed in Chapter 5, future work with respect to this study will also be focused on methods to determine true version without the need for complex equipment. For example, a digital inclinometer can be used during THR surgery for determining the apparent operative inclination. A digitised compass attached to the version arm of a MAG may therefore be an appropriate solution for determining apparent operative version.

A second limitation of the model is that it cannot be used for determining intra-operative pelvic orientation in-situ since it requires post-operative radiographs to estimate the true inclination and version required by the server. However, it can be

used as a research tool for identifying trends in pelvic positioning with respect to different surgical props and surgeons' patient positioning practices. Identifying ongoing pelvic orientation trends may help to reduce variability in post-operative acetabular orientation variability.

6.5 Conclusion

A new algorithm for estimating intra-operative pelvic orientation from apparent operative acetabular component orientation and post-operatively estimated true orientation of the acetabular component demonstrated that pelvic anterior / posterior tilt is likely to vary most intra-operatively. It was also demonstrated that the use of the TAL approach compensates for this effect. However, pelvic external / internal rotation was predicted to be the dominant threat to acetabular component mal-positioning. To maintain the acetabular component orientation to within 10° of the apparent orientation, a low threshold for pelvic adduction / abduction and external / internal rotation was predicted. Findings from this study indicate that, to compensate for intra-operative pelvic mal-positioning, when using the TAL approach, orthopaedic surgeons should typically aim for an apparent operative inclination that is 9° less than their desired true inclination.



SEVEN

Discussion

7.1 Introduction

Mal-orientation of the acetabular component can result in negative side effects such as an increased risk of dislocation^{29, 42, 63, 115} or component loosening¹²⁸⁻¹³⁰. Not only is this harmful for the patient, but it may result in the need for a revision THR. With an aging population³⁹ and increasingly younger patients seeking THR,¹⁰ it is important to achieve the correct acetabular orientation the first-time round. This will help reduce the impact of the rising THR burden.

Currently, there is a wide range of acetabular orientations reported on post-operative radiographs.²⁹⁻³¹ These angles, deviate from the angles of acetabular orientation perceived intra-operatively by the orthopaedic surgeon. This thesis focused on understanding the relationship of pelvic positioning during surgery and follow-up radiography with acetabular component placement and measurement of its orientation. In particular, it sought to answer the question of how pelvic orientation affects acetabular cup orientation in current practice and whether it can be accounted for without the use of expensive tools or additional radiation exposure.

7.2 Current Surgical Practice

From a review of current surgical practice (Objective 1, Appendix A), it was identified that 90% of orthopaedic surgeons within the UK (n=154/172) operate using *lateral decubitus* patient positioning. The most common methods for controlling operative inclination and version were a mechanical alignment guide (MAG; n = 78/154; 50.6%) and the transverse acetabular ligament (TAL; n = 82/154; 53.2%). This thesis specifically sought to discover the influence of pelvic orientation on these approaches so that new inexpensive tools could be developed to aid and minimally disrupt current surgical practice.

7.3 Theoretical Impact of Operative Pelvic Position on Intra-operative

Acetabular Component Orientation

In order to understand the tools needed to improve intra-operative pelvic orientation, it was first necessary to understand the relationship between current surgical practice, operative pelvic orientation and acetabular component mal-rotation (Chapter 3, Objective 2). This was investigated for two different popular navigation approaches: the mechanical alignment guide and TAL approach. From this study, it was apparent that an appropriate choice of surgical technique could be used to help reduce the variation in post-operative measures of acetabular orientation. In particular, use of the TAL approach exhibited greater control over true version (relative to the anterior pelvic plane) when compared to the mechanical alignment guide method (Figure 3.11). This is supported by the literature, in which the TAL approach has previously been shown to be superior to the MAG approach for controlling acetabular version in both experimental and clinical environments.^{171,176} However, with respect to inclination, both methods performed poorly when the sagittal pelvic plane was not parallel to the surgical theatre floor. This emphasises the need for tools or techniques to ensure that the pelvic sagittal plane remains parallel to the theatre floor during surgery. In particular, when using the TAL approach, both pelvic external / internal rotation (rotation about the long axis of the pelvis) and adduction / abduction (rotation about the anterior-posterior axis) were identified as the primary modes of operative pelvic orientation that would theoretically influence the discrepancy between operative and post-operative radiographic acetabular orientation (Table 3.5).

7.4 Controlling Intra-operative Pelvic Orientation

In order to minimise these operative pelvic orientations, a new technique for patient positioning was proposed (Chapter 4, Objective 3). This approach involves drawing

transverse pelvic lines on the patient's lower back for controlling pelvic adduction / abduction. A coronal alignment guide was manufactured for aiding the orthopaedic surgeon in achieving zero external / internal rotation in *lateral decubitus*.

By imposing leg-length imbalances (forcing the affected side to lift and resulting in increased pelvic adduction), a clear trend of increased pelvic adduction (in this instance, a measure of the angle between the transverse pelvic lines and a horizontal line whilst standing and thus is independent of hip side) with increased leg-length imbalance was observed when using the transverse pelvic lines (Figure 4.9). Thus, the transverse pelvic lines moved with pelvic adduction. Pelvic adduction during THR can result in a loss of acetabular coverage.

Positioning each participant in neutral using the coronal alignment guide resulted in low mean external pelvic rotation of $0.60^{\circ} \pm 0.68^{\circ}$ (-3.30° to 6.10°), highlighting the ability to achieve close to neutral pelvic rotation when using the guide. These tools represent inexpensive solutions that can be readily adapted along current surgical practice with minimal disturbance.

7.5 Accounting for Post-operative Pelvic Orientation

To establish the use of the transverse lines for reducing operative pelvic mal-rotation and thus the discrepancy between operative and post-operative measures of acetabular orientation when using the TAL approach, the transverse lines were employed in THR practice and their radiographic outcomes assessed. Before radiographic outcomes could be assessed, however, there was an imperative to establish a common radiographic reference frame of measurement (Chapter 5, objective 4). This was because the acetabular orientation projected onto an anterior-posterior radiograph has been shown to be influenced by pelvic mal-rotation in the supine position.^{19,28} In this

way an estimate of true inclination and version could be made from a single post-operative radiograph.

Using the computational tool developed in Chapter 5, most of the variation observed between apparent operative and true version (79%) was accounted for by pelvic mal-rotation and magnification errors during radiography. Conversely, only a small fraction (22%) of the variation between apparent operative and true inclination was accounted for by these factors. The majority of the variation in inclination between the operative and radiographic reference frames could not be explained as a function of radiographic supine pelvic positioning. It was thus primarily a function of the intra-operative position of the pelvis.

Use of the transverse pelvic lines to control intra-operative pelvic adduction / abduction didn't significantly alter the mean true orientation achieved when compared to standard practice. However, their use did result in a smaller number of unsafe cases (0° HD = 5, Y° HD = 1, Table 5.3). This implies that the use of the transverse pelvic lines reduced the number of outliers that would have otherwise occurred. This is similar to the results that are currently observed for CAOS. Although no significant differences in the mean acetabular orientation achieved were observed between CAOS and traditional navigation approaches¹⁸⁴⁻¹⁸⁷, CAOS has been seen to reduce the number of outliers.^{183-184,187} The use of the transverse lines is, however, cheaper to implement and can be readily adapted into current practice. It only requires the use of a surgical marker that is already present within theatre for marking the operative hip. However, as observed in Chapter 5 (Figure 5.19), reduced discrepancy between the mean apparent operative and true inclination may be achieved by altering the head down angle of the theatre table.

7.6 Target Apparent Operative Inclination

An alternative approach to altering the head down angle of the theatre table is to adjust the target apparent operative inclination that an orthopaedic surgeon employs. This also requires no additional expenses. In order to ascertain a new target apparent operative inclination, knowledge of combined operative pelvic mal-rotations are required. The solver developed in Chapter 6 (Objective 5) proved capable of predicting intra-operative pelvic orientation in the validation study of a surrogate pelvis. When applied to a clinical cohort of THR patients, the solver predicted that the pelvis tended to be internally rotated, adducted, and posteriorly tilted during surgery. These findings are supported by the available literature.^{27,193-195}

Although the earlier theoretical study (Chapter 3) identified adduction / abduction as the key rotation to be controlled, this study found that pelvic external / internal rotation was the key determinant in predicting errors in acetabular component positioning for this clinical cohort. This was likely due to the much wider variance for external / internal rotation than was found for adduction / abduction (Figure 6.6).

These findings suggest that, in order to close the remaining gap between operative and radiographic acetabular inclination, when using the TAL approach, an orthopaedic surgeon should typically aim for an apparent operative inclination that is 9° less than their intended true inclination.

7.7 Technical Novelty

This thesis has increased awareness of modal orthopedic surgical practices (Appendix A). It has expanded upon definitions for acetabular orientation (Chapter 3 and 5). Of note, these definitions highlight differences between measures of acetabular orientation in practice (apparent, relative to external landmarks) and those defined

within the literature (true, relative to the pelvis). Furthermore, this thesis provided a means a mapping apparent operative to post-operative measures of radiographic acetabular orientation through the use of novel tools (Chapter 5). This research quantified the relationship between intra-operative pelvic orientation and true acetabular orientation for two different surgical approaches (Chapter 3). This is advantageous for recommending a superior approach when compensating for intra-operative pelvic orientation; current studies within literature either analyze a single approach or neglect to mention the approach at all. This accumulated in the recommendation of new target angles for intra-operative acetabular orientation in the absence of corrective measures. Additionally, new tools were also developed to help reduce pelvic mal-positioning during patient positioning (Chapter 4).

7.8 Summary of implications for surgical practice

The discrepancy between intra-operative and post-operative radiographic acetabular component orientations can be explained as a function of pelvic orientation during both surgery and radiography. This thesis developed novel techniques to aid the orthopaedic surgeons understanding of pelvic orientation within both of these reference frames. Furthermore, it was estimated that the majority of the variation in inclination between the operative and radiographic reference frames could not be explained as a function of radiographic supine pelvic positioning. It was thus concluded to be primarily a function of the intra-operative position of the pelvis.

With respect to reducing radiographic variability as a result of operative pelvic positioning, the orthopaedic surgeon should rely on internal landmark-based approaches where possible. In this thesis, the use of the internal TAL was recommended for controlling operative version. This is a patient-specific landmark that is independent of pelvic positioning. However, TAL doesn't provide a solution

for operative inclination. With respect to variability in radiographic inclination, intra-operative pelvic external / internal rotation is of primary concern. This thesis proposed the use of transverse pelvic lines and a coronal alignment guide for monitoring these orientations during patient positioning. Both of these approaches are cost effective solutions that can be readily implemented alongside current orthopaedic practice. In the absence of an internal patient-specific landmark for controlling operative inclination or intra-operative corrective measures for pelvic mal-rotation, it was proposed within this thesis that orthopaedic surgeons should typically aim for operative inclinations that are 9° less than their intended radiographic inclination when using the TAL approach. This can result in the use of target operative inclinations (36°) that are lower than those previously recommended (45°).

As sufficient clinical outcome studies with detailed intra-operative and radiographic data accrue, the tools proposed here have the potential to assess the relation between target and achieved acetabular component orientations and their correlation with specific clinical outcomes (e.g. dislocation). This may be ultimately useful in the design of new devices.

All the above findings improve our understanding of pelvic positioning during THR, which can help reduce outliers with respect to acetabular component orientation. Provided that target orientations are appropriate to specific patients, this improved control can improve the longevity of the replaced joint, reducing the need for revision surgery and improve overall patient satisfaction.



EIGHT

Conclusions

8.1 Conclusions

This thesis focused on understanding the relationship of pelvic positioning during surgery and follow-up radiography with placement and measurement of acetabular component orientation. The specific research question formulated with respect to this overall aim was “how pelvic orientation affects acetabular cup orientation in current practice and whether it can be accounted for without the use of expensive tools or additional radiation exposure?”. The original objectives (Section 2.9) and the corresponding conclusions drawn from the work carried out in relation to each of them are summarised below.

1. Statistically analyse the current state of the art in surgical hip props, patient positioning methods and surgical techniques in order to identify mechanisms in modal current practice that influence cup orientation as a result of pelvic positioning (Appendix A).
 - Results of a survey circulated to members of the British Orthopaedic Society demonstrated that use of a mechanical alignment guide (MAG) or the transverse acetabular ligament (TAL) approach were the primary methods for controlling operative acetabular orientation with patients in the *lateral decubitus* position (Appendix A).
2. Establish, theoretically, the impact of intra-operative pelvic movement on acetabular orientation with relation to current practice. This will enable primary modes of intra-operative pelvic mal-rotation that contribute to the variance observed between operative and radiographic measures of acetabular orientation to be identified.

- Pelvic adduction / abduction and external / internal rotation are the primary modes of pelvic operative orientation that theoretically influence changes in true inclination (and thus radiographic variability).
 - Because both the MAG and TAL approach rely on the use of the external theatre floor for controlling apparent operative *inclination*, they are both subject to the same errors for true inclination (and thus radiographic variability) due to operative pelvic position.
 - Theoretical models demonstrated that the TAL approach controls operative *version* relative to the internal patient-specific anatomy and is thus independent of operative pelvic positioning, unlike the MAG approach. The TAL approach is thus recommended for controlling operative version and reducing radiographic variability.
3. Having identified the key modes of pelvic mal-rotation, develop, trial, and evaluate a technique for aiding the surgeon in controlling pelvic position and orientating the acetabular component intra-operatively with respect to these primary modes of intra-operative pelvic mal-rotation.
- Transverse lines drawn on the patients lower back using a readily available surgical marker for monitoring pelvic adduction / abduction proved to be an inexpensive technique for monitoring operative pelvic adduction / abduction and external / internal rotation.
 - Use of a newly developed coronal alignment guide for monitoring pelvic external / internal rotation proved capable of achieving close to neutral pelvic rotation.
4. Improve post-operative assessment of acetabular component placement without the use of a CT scan or additional radiographic views. Identify the impact of

magnification errors and radiographic pelvic positioning on the observed differences between the operative and radiographic measures of acetabular orientation and estimate true orientation with respect to the pelvic reference frame.

- Applying the algorithms developed in Chapter 5 predicted that, in practice, the pelvis tends to be anteriorly tilted during radiography. Due to the large range of anterior tilts reported, and the fact that anterior tilt reduces the projected 2D radiographic version, 3D correction is a requirement in order to minimise radiographic variability.
 - The majority of the variance (79%) between apparent operative and true *version* was accounted for by radiographic pelvic mal-rotation and magnification error.
 - In contrast, only 22% of the variance between apparent operative and true *inclination* was accounted for by radiographic pelvic mal-rotation and magnification error. The majority of the discrepancy between apparent operative and true inclination was predicted to result from intra-operative pelvic positioning.
 - High values of true version have greater impact on 2D radiographic inclination errors than previously reported within literature.
 - Transverse pelvic lines can be used to reduce outliers with respect to true inclination. However, better clinical gains may be attained by altering the head down angle of the theatre table or by targeting an appropriate apparent operative inclination.
5. Combine the theoretical understanding of pelvic mal-rotation (Objective 2) with the post-operative assessment tool (Objective 4) to estimate intra-operative pelvic orientations without the use of CAOS. This tool can then be applied to a clinical

cohort to identify primary modes of intra-operative pelvic mal-rotation that contribute most to the variance observed between operative and radiographic measures of acetabular orientation in clinical practice.

- Application of the solver developed in Chapter 6 predicted that, in practice, the pelvis tends to be internally rotated, adducted, and posteriorly tilted during surgery.
- Clinically, when using the TAL approach, pelvic external / internal rotation was identified as the only mode of operative pelvic orientation that influenced the discrepancy between operative and radiographic measures of acetabular orientation.
- When using either the TAL or MAG approaches, without correction for operative pelvic orientation (Objective 3), orthopaedic surgeons should aim for an apparent operative inclination that is approximately 9° lower than their intended true inclination. Thus, if targeting a true inclination of 45° , a target apparent operative inclination of 36° should be employed.

8.1.1 Summary of conclusions to guide surgical practice

The findings of this work suggest that, in order to reduce radiographic variability due to pelvic positioning, orthopaedic surgeons should

- Use internal landmarks where feasible, e.g. the use of the transverse acetabular ligament. These landmarks are independent of operative pelvic positioning.
- Use transverse pelvic lines drawn on the patient's back to control pelvic adduction and a coronal alignment guide to control pelvic rotation.
- In the absence of corrective measures for intra-operative pelvic orientation (Objective 3), aim for an apparent operative inclination that is 9° less than their

intended true inclination when using either the TAL or MAG approaches. To ensure an exact target, a digital inclinometer should be employed.

- Ensure all 2D measures of radiographic acetabular orientation are converted into true 3D measures. This will account for the magnification errors due to radiographic pelvic positioning.

All of the above suggestions can be adapted into current surgical practice with minimal expense and without additional radiation exposure.



NINE

Future Work

9.1 Controlling Intra-operative Pelvic Orientation

In Chapter 6, pelvic external / internal rotation was identified as the primary mode of pelvic operative orientation that influenced the discrepancy between apparent and true inclination. In Chapter 4, a new coronal alignment guide was developed that could be used to reduce the degree of pelvic external / internal rotation. It was not viable to test the use of the coronal alignment guide within a clinical setting within the time frame of this research. Consequently future work with respect to the alignment guide could involve an ethically approved clinical study in which the alignment guide is used to align patients undergoing THR. As with the use of the transverse pelvic lines, success of the approach could be monitored via radiographic assessment of acetabular orientation.

9.2 Accounting for Post-operative Radiographic Pelvic Orientation

If the true version prior to the radiograph is known, the computational tool developed in Chapter 5 may be simplified by eliminating the secondary stage (reconstruction of the pelvis). The introduction of a pubis symphysis reference arm (Chapter 5, Figure 5.21) alongside a digital compass, as previously discussed, could also be used to approximate an intra-operative measure of true version. Future work may thus involve the design and validation of these tools.

Alongside the simplification of the computational tool, future work may entail further clinical validation. Within Chapter 5, the computational tool was validated theoretically. Although the tool provided clinically relevant outputs, paired CTs and radiographs would be required to clinically validate the computational tool.

9.3 Target Apparent Operative Inclination

In Chapter 6, a new computational tool was developed for predicting intra-operative pelvic orientation. The tool was subsequently used to determine a new target apparent operative inclination. Further clinical validation of the tool may be employed by comparing the operative pelvic orientations predicted by the solver with intra-operative CT measurements (e.g. by analysing data from image-based CAOS procedures).



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Appendix A

Patient positioning and cup orientation during total hip arthroplasty:**Assessment of current UK practice****Abstract****Introduction**

Acetabular cup orientation during total hip arthroplasty (THA) remains a challenge. This is influenced by patient positioning during surgery and by the method used to orientate the acetabular cup. The aim of this study was to assess current UK practice for patient positioning and cup orientation, particularly with respect to patient supports and techniques used to achieve target version and inclination.

Method

A literature review and pilot study were initially conducted to develop the questionnaire which was completed by members of the British Hip Society (n = 183). As the majority of THA surgical procedures within the UK are performed with the patient in *lateral decubitus*, orthopaedic surgeons who operated with the patient in the supine position were excluded (n = 18); a further 6% were incomplete and also excluded (n = 11).

Results

Of those who operated in *lateral decubitus*, 76.6% (n = 118/154) used the posterior approach. Only 31% (n = 47/154) considered their supports to be completely rigid. More than 35% (n = 55/154) were unhappy with the supports that they presently use. The most common methods for controlling operative inclination and version were a mechanical alignment guide (MAG; n=78/154; 50.6%) and the transverse acetabular ligament (TAL; n = 82/154; 53.2%]); 31.2% (48/154) used a freehand technique to control operative inclination.

Conclusion

Limited studies have been conducted whereby patient supports have been analysed and key design principles outlined. With 35.7% of orthopaedic surgeons having issues with their current supports, a greater awareness of essential characteristics for patient supports is required.

1.0 Introduction

There are several approaches available to an orthopaedic surgeon for controlling intra-operative acetabular orientation.¹ With respect to operative inclination, a mechanical alignment guide (MAG) or freehand approach may be used in reference to the surgical theatre floor, with the latter acting as an “external” landmark. The MAG has been shown to reduce acetabular positioning errors relative to a fixed target for intra-operative inclination when compared to a freehand technique.²⁻⁵ However, both techniques are potentially compromised by using the external theatre floor. For the external theatre floor to be a viable landmark for controlling operative inclination, the internal pelvic sagittal plane has to be parallel to the external theatre floor. This ensures that the two anterior superior iliac spines are vertical with respect to each other. Adduction (Figure 1a) and or internal rotation (Figure 1b) of the upper hemi-pelvis results in the apparent operative inclination (i.e. angle between the introducer and theatre floor) being less than the true inclination (i.e. angle between the introducer and the sagittal plane). Consequently, a higher radiographic inclination will also be observed.

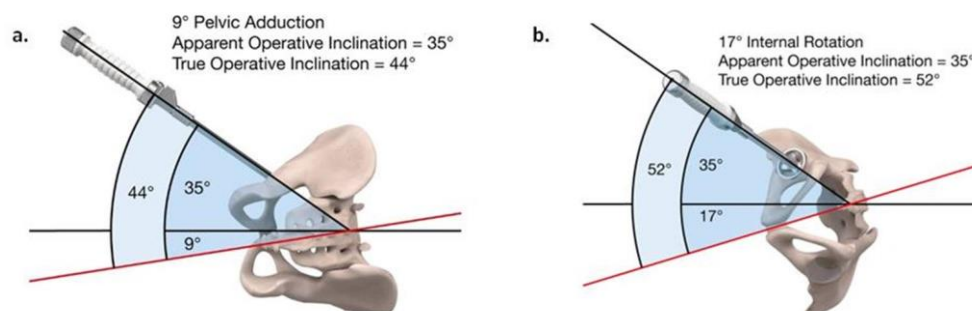


Figure 1: Intra-operative a) adduction and b) internal rotation increase true inclination over apparent operative inclination

For operative version, a MAG or freehand approach may be used in reference to the theatre table longitudinal axis, with the latter acting as an “external” landmark. In this instance, the use of the external theatre table longitudinal axis is compromised if the angle between it and the internal anterior pelvic plane (APP) is unknown. The use of internal patient-specific landmarks, such as the transverse acetabular ligament (TAL),⁶ can compensate for intra-operative variation in pelvic tilt (i.e. rotation about the pelvic transverse axis). TAL has been associated with a reduced risk of dislocation.⁶

With respect to patient positioning, it is clearly important to have an understanding of the intra-operative position of the pelvis relative to the external theatre when implanting the acetabular component. Milone et al⁷ obtained absolute acetabular cup placement errors of up to 20° when using external landmarks. This was particularly important for operative version, with 22% (n = 22/100) of their cases being placed more than 10° away from their intended target. They concluded that patient positioning could not be relied on when orientating the acetabular cup. Grammatopoulos et al⁸ have illustrated that pelvic position deviates from its intended position during both pre-operative patient positioning and intra-operatively. Subsequent intra-operative movement may result from inadequate fixation and/or retraction forces during THA.⁹ Grammatopoulos et al⁸ also observed that the choice of patient support could be used to reduce the extent of pelvic movement. Although different supports were used, this finding was maintained by Iwakiri et al.¹⁰

Traditionally with respect to acetabular cup orientation, orthopaedic surgeons have targeted the Lewinnek safe zone,¹¹ which recommends $40 \pm 10^\circ$ of radiographic inclination and $15 \pm 10^\circ$ of radiographic version (Figure 2). However, this recommendation was based on observations from a study of only nine dislocations and

more recent studies have shown that up to 60% ($n = 76/127$) of dislocations can be within the Lewinnek safe zone.¹²⁻¹⁴ Although alternate safe zones have been proposed, a general consensus from the orthopaedic surgical community has not been reached.^{13,15} Nevertheless, several clinical studies have reported that mal-positioning of the acetabular cup has been associated with increased risk of dislocation^{11,12,16-21} and a greater rate of wear.²²⁻³⁰

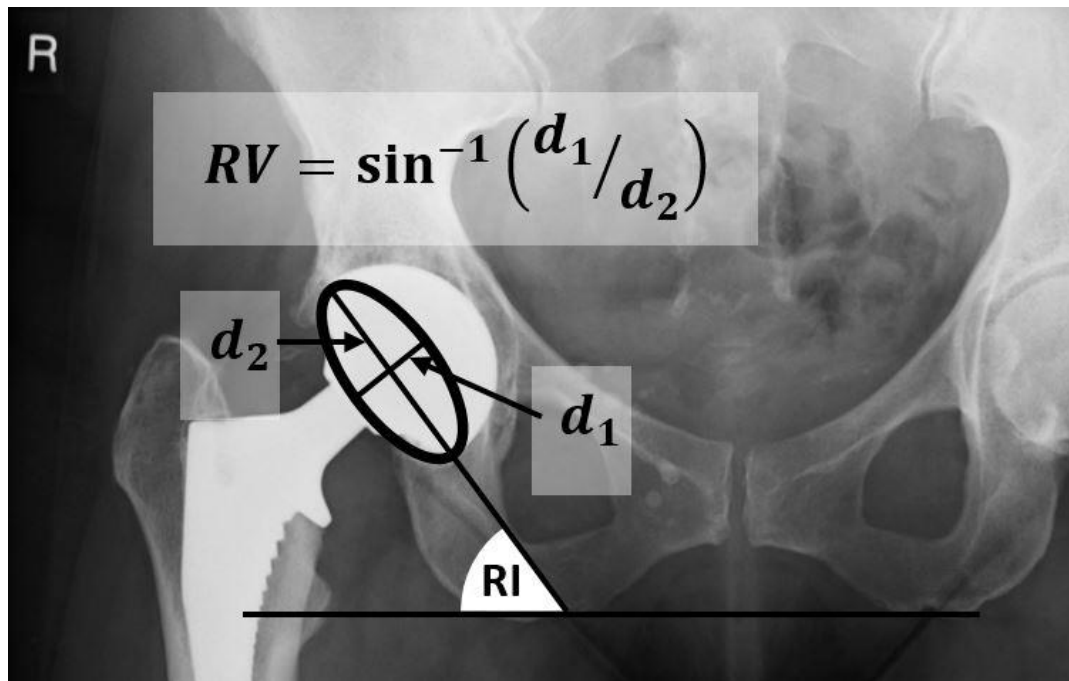


Figure 2: Antero-posterior view of pelvis showing radiographic acetabular inclination (RI) and version (RV).

A one-size-fits-all target acetabular cup orientation may not be applicable due to variations in the native orientation of the acetabulum between patients. Archbold et al³¹ reported that the native variation in TAL-*labrum* version relative to the anterior pelvic plane was over 30°. Goudie et al found that 75% of their cohort ($n = 49/65$) had a native acetabular orientation outside the Lewinnek safe zone.³² Additionally, there was a significant difference in the extent of acetabular radiographic version between

male and female cohorts. These conclusions are in agreement with the findings by Murtha et al.³³

The aim of this research was to establish current UK surgical practice with respect to pre-operative patient positioning in *lateral decubitus*, as the majority of THA surgical procedures within the UK are performed with the patient in this position,³⁴ and secondly to determine the techniques used to achieve target version and inclination. The research aim was tested by way of a questionnaire, which was completed by members of the British Hip Society within the period between April and June of 2014.

2.0 Method

A review of the commercially available apparatus for intra-operative pelvic positioning in *lateral decubitus* was conducted by assessing commercially available technology and reviewing intellectual property applications using Google Patents. A separate literature review was performed to learn the most commonly used surgical methods for determining intra-operative cup orientation, namely inclination and version, using PubMed and the UK National Joint Registry (NJR).³⁴ Key search words included: pelvis, pelvic, orientation, position, patient positioning, hip replacement, hip arthroplasty, supports, acetabular, and acetabulum. Information collated from this literature review was used to support the development of an initial sample questionnaire for establishing current UK surgical practice and to comprehend how current technology meets user needs.

From the NJR,³⁴ it was apparent that the greatest majority (91%) of THA procedures conducted within the UK were performed with the patient in the *lateral decubitus* position. Given that our interest focused on surgical supports, it was decided to exclude orthopaedic surgeons who operated with the patient in the supine position from the study.

The initial questionnaire facilitated technical feedback from a sample cohort of the orthopaedic community (n = 21), which was used to refine the questions for the final questionnaire. This initial questionnaire was completed by orthopaedic surgeons from five different orthopaedic centres from across the UK.

An extended questionnaire³⁵ was developed using SurveyMonkey® (SurveyMonkey Inc., USA), which facilitated easier access to the survey, more reliable data collection

and the efficient use of pathway logic. The extended questionnaire was reviewed by a statistician to eliminate bias and to ensure the practicality of the questionnaire.

With the permission and assistance of the British Hip Society, a web link to the questionnaire was emailed to all its members. Descriptive statistics (frequency plots, mean, standard deviation, and mode) were calculated using Microsoft Excel (Microsoft Corporation, USA).

3.0 Results

A total of 183 members from the British Hip Society responded to the extended questionnaire via SurveyMonkey®. Eleven (6%) surveys were returned incomplete and thus excluded from analysis. A further 18 (9.8%) surveys were excluded because the orthopaedic surgeon operated with the patient in the supine position, which resulted in 154 questionnaires (84%) being considered for analysis.

The maximum number of THA procedures performed by an orthopaedic surgeon per annum was 500 and the minimum performed was 20. The mean number (\pm SD) of THA procedures performed per annum was 142 (\pm 85). The most commonly reported period of surgical practice was 15 years or more ($n = 55/154$; 35.7%, Figure 3).

The most popular choice of anterior surgical supports for positioning the patient intra-operatively was a double “goal post” design ($n = 45/154$; 29.2%, Figure 4a). The two posts engage the anterior superior iliac spines (ASISs) and can be moved both horizontally and vertically relative to each other. The second preferred choice was a single post design for engaging the upper ASIS using a universal ball joint ($n = 33/154$; 21.4%). In addition to the popular double ASIS anterior support design, other pelvic supports within the questionnaire also featured the use of two ASIS supports.

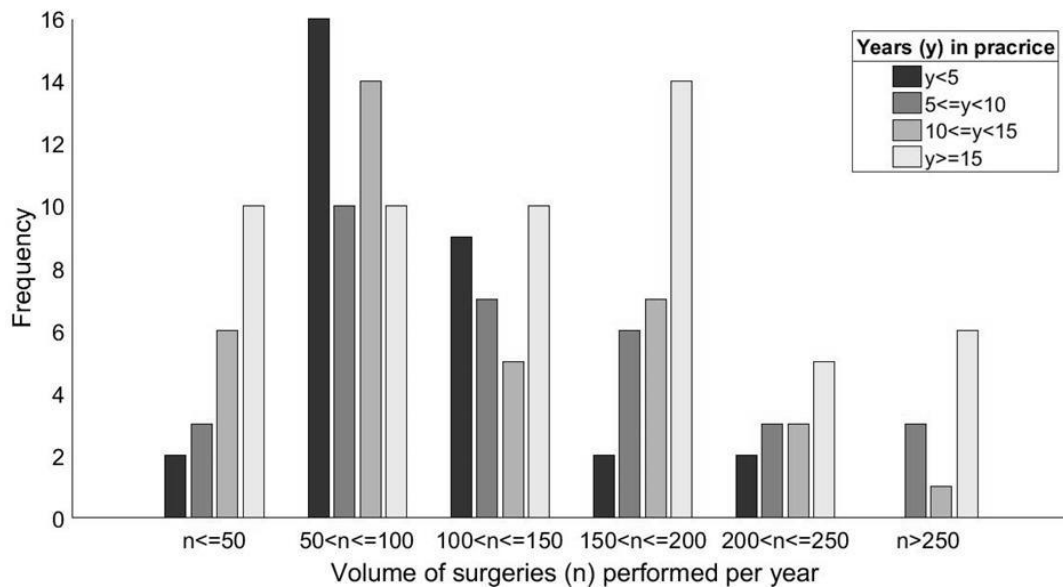


Figure 3: Surgical THA experience of UK orthopaedic surgeons as a function of the number of procedures performed per year and years in practice.

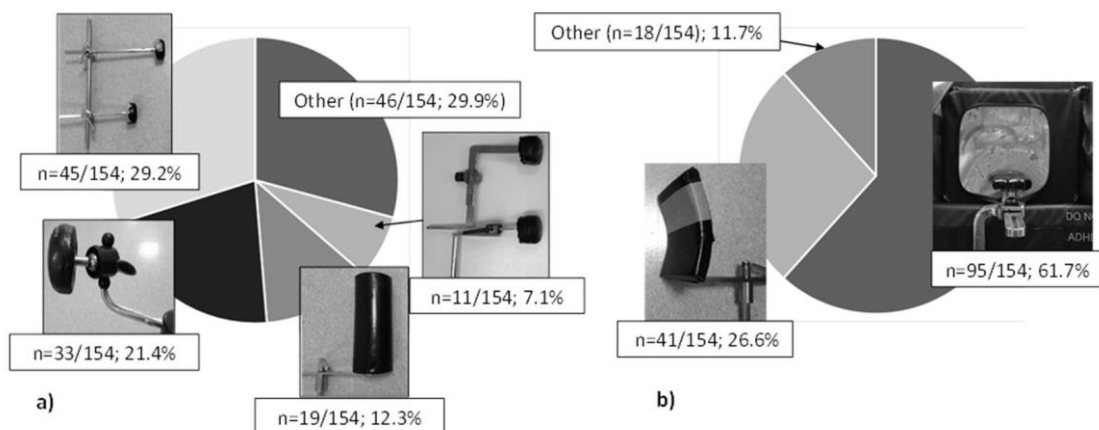


Figure 4: a) Anterior and b) Posterior surgical hip supports used in practice.

In total, 44.1% ($n = 68/154$) of the respondents used anterior supports that engaged both of the ASISs. Of those respondents using two ASIS posts, irrespective of design ($n = 68/154$; 44.1%), 72.0% ($n = 49/68$) used two ASIS supports that could be moved both horizontally and vertically relative to each other, while only 23.5% ($n = 16/68$) used two ASIS supports that could only be moved vertically. With this latter support type, if both ASISs are engaged then the pelvic sagittal plane should be parallel to the

theatre floor. The remainder of double ASIS surgical supports considered were either fixed ($n = 1/68$; 1.4%) or could be moved horizontally ($n = 2/68$; 2.9%) relative to each other.

With respect to posterior surgical supports, the most common style was a flat faced design ($n = 95/154$; 61.7%, Figure 4b). When positioning the posterior support, most orthopaedic surgeons aimed to engage the sacrum ($n = 81/154$; 52.6%). The majority of respondents were directly involved or supervised initial patient positioning within the surgical supports ($n = 151/154$; 98.0%).

Within the questionnaire, the supports were classified as being rigid if the “supports never give way and do not show signs of movement intra-operatively or at the end of surgery”. In response, only 30.5% of respondents ($47/154$) stated that their supports (both anterior and posterior) were completely rigid. The majority of respondents ($120/154$; 77.9%) were unaware of the manufacturer or the trade name of the supports being used during THA.

The most reported issue with respect to surgical prop design was that their placement was limited by gaps in the rails of the surgical tables ($n = 44/154$). With respect to perceived limitations, 47.4% ($n=73/154$) reported no issues with their supports. However, respondents noted some negative side-effects that included: skin break ($n=23/154$; 14.9%), bruising ($n=19/154$; 12.3%) and nerve injury ($n=13/154$; 8.4%). Respondents reported skin break and bruising around the pubis symphysis and anterior superior iliac regions, whilst nerve injury was noted as occurring to the *lateral cutaneous* nerve of the thigh.

The majority of orthopaedic surgeons ($n = 121/154$; 78.6%) reported that the surgical supports were not radiolucent. However, most of these surgeons ($n = 112/154$; 72.7%)

also stated that they never used intra-operative radiographic imaging. More than a third of the respondents ($n = 55/154$; 35.7%) would like to change the surgical supports they currently use during THA.

With regard to surgical approach used during THA, 76.6% (118/154) were posterior and 22% lateral (34/154). To control operative inclination, 50.6% (78/154) used a MAG and 31.2% (48/154) used a freehand technique. Through extrapolation, 83.1% (128/154) used the theatre floor as an external landmark (Table 1). The mean target radiographic inclination was 42.6° ($\pm 2.94^\circ$, min = 30° , max = 52°) which fits within the Lewinnek safe zone. To control operative version, 52.3% (82/154) used the TAL (Table 1).

Table 1. Primary guidance approach for obtaining intra-operative acetabular a) inclination and b) version.

	Approach	n / 154	%
Operative Inclination	Mechanical Alignment Guide	78	50.6
	Freehand	48	31.2
	Internal Landmarks	24	15.6
	Computer Aided Surgery	2	1.3
	Other	2	1.3
Operative Version	Transverse Acetabular Ligament	82	53.2
	Freehand	38	24.7
	Mechanical Alignment Guide	24	15.6
	Other Internal Landmarks	10	6.5

4.0 Discussion

The aim of this research was to establish current UK surgical practice with respect to preoperative patient positioning in *lateral decubitus*, and secondly the techniques used to achieve target version and inclination. The main outcomes will be discussed below.

With respect to patient positioning and anterior supports, 21.4% of orthopaedic surgeons used a single support placed on the uppermost ASIS. Grammatopoulos et al⁸ demonstrated that the use of two ASIS supports reduced intraoperative pelvic movement when compared to a single ASIS brace arm. They concluded that the use of a single ASIS support combined with a posterior support over the lumbosacral spine tended to force the upper hemi-pelvis to externally rotate. When using the theatre floor as an external landmark, this would result in a reduction in the expected radiographic inclination.³⁶ Although 44% (n=68/154) of orthopaedic surgeons in the UK used two ASIS supports, only 10.4% (16/154) adopted a support system in which the horizontal bars were maintained at the same length. As with the use of a single ASIS brace arm, for two horizontally adjustable ASIS brace arms, over-extension of one ASIS brace arm relative to the other will induce pelvic rotation about the longitudinal axis. Thus, it would appear logical that the pelvis would ideally be held in neutral rotation by using two anterior ASIS brace arms that are of equal length relative to each other, but can be adjusted vertically to allow for different inter-ASIS distances.³⁷⁻³⁸

The use of two ASIS brace arms that are maintained at the same length does not necessarily ensure that the pelvic sagittal plane is parallel to the theatre floor. Firstly, both ASISs have to be engaged, but that only ensures that they are vertical with respect to each other in the pelvic coronal plane. They may not be vertical within the pelvic transverse plane and, consequently, the pelvis may be adducted or abducted. Adduction appears as a lowering of the operative hip towards the surgical theatre floor (positive), whilst abduction represents the opposite motion (negative). Grammatopoulos et al⁸ indicated a mean adduction angle of 4° (2SD±12), at patient set up, followed by intra-operative movement (\bar{x} = 9°). This finding is supported by the current questionnaire, with only 31% (n=47/154) considering their supports to be

completely rigid and, thus, maintaining a stable pelvic position. Use of the theatre floor as an external landmark in this instance (using a mechanical alignment guide or freehand technique), would result in a radiographic inclination approximately 13° higher than expected.³⁶ It is expected that this would have a negative effect on outcomes as high radiographic inclination angles contribute to component wear²²⁻²³ and risk of dislocation.¹⁶

The results of the questionnaire indicated that most surgeons relied on a mechanical alignment guide or the freehand technique to control inclination (n = 126/154; 81.8%). Positioning relative to the transverse acetabular ligament was the most common method to control version, albeit with a smaller majority (n = 82/154; 53.2% for transverse acetabular ligament vs. n = 62/154; 40.2% for mechanical alignment guide plus the freehand technique). Thus, there are many orthopaedic surgeons that rely on the use of external landmarks for controlling both operative inclination (theatre floor) and version (long axis of the patient or theatre table). For operative inclination, the use of a mechanical alignment guide has been shown to increase the surgeon's ability to achieve their target orientation relative to the theatre floor when compared to using the freehand technique.²⁻⁵ However, as discussed, it is important to ensure that the pelvic sagittal plane is parallel to the theatre floor at the time of acetabular cup insertion by correct patient positioning and by using appropriate patient supports. With regard to version, in agreement with the findings of this study, we feel that using an internal landmark such as the transverse acetabular ligament is a more appropriate choice for controlling version. The transverse acetabular ligament is a patient specific landmark,³¹ independent of pelvic orientation, which has been associated with an increased probability of safe cup placement.³⁹⁻⁴¹

Approximately 78% of the orthopaedic surgeons ($n = 120/154$) were unaware of the specific brand or manufacturer of the surgical supports that they used during THA. This is possibly because orthopaedic surgeons may not have a principal role in surgical support selection or procurement. Interestingly, 35.7% ($n = 55/154$) of the respondents highlighted that they would like to improve the surgical supports they currently use during THA. However, financial constraints within individual orthopaedic centres may be a limiting factor in selection and procurement of preferred surgical supports.

Conclusion

A large volume of orthopaedic surgeons rely on freehand or mechanical alignment guide techniques, which use external landmarks for controlling operative inclination ($n = 126/154$; 81.8%) and operative version ($n = 62/154$; 40.3%). When using external landmarks for guiding the acetabular cup, the intra-operative position of the pelvis relative to these landmarks must be known. This may be achieved via suitable patient fixation supports. However, from the orthopaedic perspective, existing supports may lack rigidity ($n = 107/154$; 69%) and their placement can be limited by the rails in the surgical table ($n = 44/154$). There are few studies that investigate the impact of surgical support design on intra-operative pelvic position.^{7-8,10} Of these studies, the number of designs investigated within each study is limited. With 35.7% ($n = 55/154$) of orthopaedic surgeons unhappy with their current supports, further studies are required to help inform the orthopaedic community with respect to support choice. Going forward, new supports for stabilising the pelvis or affordable intra-operative techniques for monitoring pelvis stabilisation are required.

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Appendix B

Appendix B – TAL Axis Inclination Solver

The following problem was minimised using the `fmincon` function in MATLAB (2015b, The MathWorks Inc., USA).

- Translate rotated TAL axis (T_R) so that its current midpoint (m) becomes aligned with the Cartesian origin.
 - $T_O = T_R - m$
- Determine the angle between the T_O axis projected onto the x-z plane (T_{xz}) and the z-axis (\hat{e}_3), θ_1 .
 - $T_{xz} = \begin{bmatrix} T_{Ox} \\ 0 \\ T_{Oz} \end{bmatrix}$
 - $\theta_1 = \cos^{-1}(\hat{e}_3 \cdot T_{xz})$
- Rotate by θ_1 so that the T_O axis is now co-planar with y-z plane (T_{yz}).
 - $T_{yz} = \text{roty}(\theta_1) * T_O$
- Determine angle between the T_{yz} axis and z-axis, θ_2 .
 - $\theta_2 = \cos^{-1}(\hat{e}_3 \cdot T_{yz})$
- Rotate by θ_2 so that axis is now coincident with z-axis (T_z).
 - $T_z = \text{rotx}(\theta_2) * T_{yz}$
- Whilst β is not equal to AOI:
 - The introducer is initially treated as a unit vector coincident with the x-axis (\hat{e}_1). Rotate introducer (I) by α about the T_z or z-axis.
 - $I = \text{rotz}(\alpha) * \hat{e}_1$
 - Reverse the orientation of the TAL axis back to T_R and obtain the apparent orientation of the introducer I_A .
 - $I = \text{roty}(-\theta_1) * \text{rotx}(-\theta_2) * I$

- $I_A = I + m$

- Determine if α was sufficient to match the Apparent Operative

Inclination to the target operative inclination relative to the theatre floor.

- $I_{Axz} = \begin{bmatrix} I_{Ax} \\ 0 \\ I_{Az} \end{bmatrix}$

- $f(\alpha) = \beta = \theta_{OI} - \cos^{-1}(I_A \cdot I_{Axz})$



Appendix C

Appendix C – Transverse Pelvic Line Study**PARTICIPANT INFORMATION SHEET (Patient)****Evaluation of pelvic position in total hip replacement surgery**

We would like to invite you to take part in a research study. Before you decide you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully and talk to others about the study if you wish.

The aim of this information sheet is to tell you the purpose of this study and what will happen to you if you take part. Ask us if there is anything that is not clear or if you would like more information. First of all just to reassure you that the research will cause no pain and does not involve needles or taking any drugs.

What is the purpose of the study?

A Total Hip Replacement is one of the most frequent orthopaedic procedures performed. The main purpose of a hip replacement is to decrease pain. It is a very successful operation that involves replacing the old joint with a new part in the pelvis and one in the femur or thigh bone. Problems can arise if the new part in the pelvis is not pointing in the right direction. An example of such a problem is an increased risk of dislocation. The position of the pelvis during the operation is very important but it is often hard for the surgeon to know exactly where the pelvis is during the operation.

This study will look at how the pelvis moves when in positions that a patient would be in during a hip replacement. There will be two groups. The first group will be patients who are waiting for their operation. The second group will be volunteers

who have no hip problems. There will be equal numbers in each group. We are hoping to have 34 people in each group.

These results will help the surgeon to put the new parts the best possible place and so help decrease the number of problems. This research is being carried out as part of a PhD in Biomechanical Engineering at Queen's University Belfast which is looking at Total Hip Replacements and trying to improve how our patients do after their operation.

Why have I been invited?

We are inviting you to take part in this study as you are on the waiting list for a hip replacement with Professor Beverland and could attend an appointment at Musgrave Park Hospital without difficulty. You also meet the following criteria: you are aged between 21 and 80, you haven't had any previous hip or knee surgery, you have no known difference in your leg length and you are sufficiently mobile to take part.

Do I have to take part?

No, only if you would like to help us with the research. You will still have exactly the same treatment or standard of care as those patients who do take part.

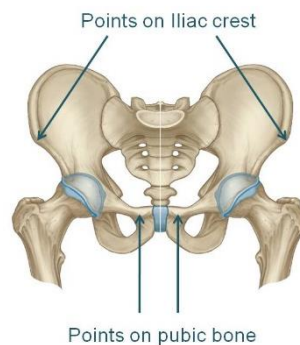
What will happen to me if I take part?

If you decide to participate, we will arrange a date and time that suits you to come to Musgrave Park Hospital. Upon arrival you will be given this information sheet to re-read and then you will be able to ask any extra questions that you may have. Then when you are sure you are happy to go ahead you will be asked to sign a consent form.

First of all we will measure your height and weight. You will then be asked to sit on an operating table in an enclosed cubicle. There will be a step to help you to get onto the table and two study investigators will help you.

One of the investigators will then measure your circumference around your middle (see picture below) using a measuring tape. To do this the study investigator will need

to feel for the bony points around your pelvis. This will be done above your clothes. In addition lines will be drawn on your lower back using a marker that is safe to use on skin and a ruler. These lines on your back will help us monitor the movement of the pelvis. In order to visualise these lines, you will have to expose your lower back by rolling your top up a little and by lowering your trousers slightly. If you feel more comfortable with a male or female investigator doing this part of the study we can arrange this if you tell us beforehand. It is advised that you wear loose fitting trousers for the study. Once these lines have been drawn, a photograph will be taken of your back. Your face will not be included in this or any other photograph taken during the study.



You will then be asked to lie on your side on the table. You may be moved into the correct position by a study investigator and another photograph will be taken of your back. We will then put supports on your back and tummy to secure you and another photograph of your back will be taken. This will be repeated two more times with two different types of surface, one harder and one softer than the usual operating table surface.

Next you will have to stand on the ground with a block under one of your feet and a photograph of your back will be taken. This will be repeated for the other foot. Finally you will be asked to stand up straight and slide your hand down one side towards your knee. A photograph will be taken of your back. This will be repeated for the other side. The whole study should take approximately 30-40 minutes at most. There will be at least two members of the research team present at all times. Your privacy and dignity will be maintained at all times.

What are the potential disadvantages and risks of taking part?

Because all participants have to lie on an operating table, there is a very small risk of falling off the table. This risk is minimised by having step aid to make it easier to get up onto the table, also there will be two members of the research team to help you get on and off the table if you need it. It is very unlikely this will happen. Also, because you are being asked to stand on blocks there is a small risk of tripping. The height of the block is chosen with respect to your height, however, the tallest block is no more than 2 inches and you will have two investigators with you at all times. The blocks will also be placed on a non-slip mat to avoid any movement during the study.

What are the possible benefits of taking part?

There are no immediate benefits to you taking part but the results of this study will help surgeons to improve hip replacement surgery in the future for other patients.

Will my taking part in the study be kept confidential?

Yes. All information that is collected during the research will be kept strictly confidential and will not be available to anybody outside of the research team. The information will be kept securely according to the standard procedures of the Belfast Trust and Queen's University of Belfast.

What will happen to the results of the research study?

We plan to use the results to find out the importance of a patient's pelvic position during hip operations. We would hope to publish any results in scientific journals and present them at local and international meetings. The identity of any participant will not be disclosed when the results are published. In particular results from this study will form an important part of a PhD thesis.

What will happen if I do not want to carry on with the study?

You can withdraw from the study at any time. Information and results collected until the time you withdraw may still be used.

Who is funding the research?

This study is being funded by the Belfast Arthroplasty Research Trust (BART) and will use existing staff and resources at the Outcomes Unit here at Musgrave Park Hospital.

Who are the study investigators?

The study investigators are:

Professor David Beverland (consultant orthopaedic surgeon, Musgrave Park Hospital)

Mr Dennis Molloy (consultant orthopaedic surgeon, Musgrave Park Hospital)

Dr Janet Hill (Biomechanical engineer working at Musgrave Park Hospital)

Dr Janine Blaney (Research analyst, Musgrave Park Hospital)

Mr Aidan Rooney (Physiotherapist, Musgrave Park Hospital)

Miss Megan Rutherford (PhD Student from Queen's University Belfast)

Dr Nicholas Dunne (Reader, Queen's University Belfast)

Dr Alex Lennon (Lecturer, Queen's University Belfast)

Who has reviewed the study?

All research in the NHS is looked at by an independent group of people, called a Research Ethics Committee to protect your safety, rights, wellbeing and dignity.

Further information and contact details

If you have any questions about this research study you can contact Dr Seamus O'Brien, Outcomes Unit Manager, Musgrave Park Hospital at 02895 047387. If you would an independent contact to seek general advice about taking part in research you can contact Professor James Nixon, 02895 046276.

This information sheet is your copy to take away and keep.



PARTICIPANT INFORMATION SHEET (Control)

Evaluation of pelvic position in total hip replacement surgery

We would like to invite you to take part in a research study. Before you decide you need to understand why the research is being done and what it would involve for you. Please take time to read the following information carefully and talk to others about the study if you wish.

The aim of this information sheet is to tell you the purpose of this study and what will happen to you if you take part. Ask us if there is anything that is not clear or if you would like more information. First of all just to reassure you that the research will cause no pain and does not involve needles or taking any drugs.

What is the purpose of the study?

A Total Hip Replacement is one of the most frequent orthopaedic procedures performed. The main purpose of a hip replacement is to decrease pain. It is a very successful operation that involves replacing the old joint with a new part in the pelvis and one in the femur or thigh bone. Problems can arise if the new part in the pelvis is not pointing in the right direction. An example of such a problem is an increased risk of dislocation. The position of the pelvis during the operation is very important but it is often hard for the surgeon to know exactly where the pelvis is during the operation.

This study will look at how the pelvis moves when in positions that a patient would be in during a hip replacement. There will be two groups. The first group will be patients who are waiting for their operation. The second group will be volunteers who have no hip problems. There will be equal numbers in each group. We are hoping to have 34 people in each group.

These results will help the surgeon to put the new parts the best possible place and so help decrease the number of problems. This research is being carried out as part of a PhD in Biomechanical Engineering at Queen's University Belfast which is looking at Total Hip Replacements and trying to improve how our patients do after their operation.

Why have I been invited?

We are inviting you to participate in this study as you are within the age range of 21 to 80 years and could attend an appointment at Musgrave Park Hospital without difficulty. In addition you haven't had any previous hip or knee surgery, you do not currently suffer from hip, knee or back pain, you have no perceived leg length discrepancies and you are sufficiently mobile to take part.

Do I have to take part?

No, only if you would like to help us with the research.

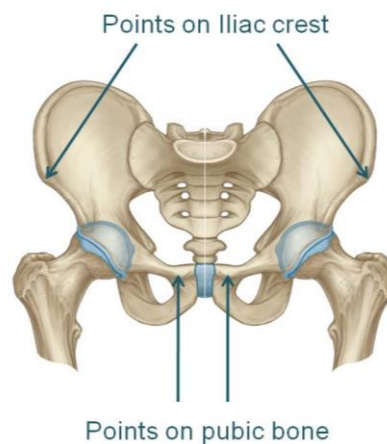
What will happen to me if I take part?

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comfortable with a male or female investigator doing this part of the study we can arrange this if you tell us beforehand. It is advised that you wear loose fitting trousers for the study. Once these lines have been drawn, a photograph will be taken of your back. Your face will not be included in this or any other photograph taken during the study.



You will then be asked to lie on your side on the table. You may be moved into the correct position by a study investigator and another photograph will be taken of your back. We will then put supports on your back and tummy to secure you and another photograph of your back will be taken. This will be repeated two more times with two different types of surface, one harder and one softer than the usual operating table surface.

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What are the potential disadvantages and risks of taking part?

Because all participants have to lie on an operating table, there is a very small risk of falling off the table. This risk is minimised by having step aid to make it easier to get

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What are the possible benefits of taking part?

There are no immediate benefits to you taking part but the results of this study will help surgeons to improve hip replacement surgery in the future for other patients.

Will my taking part in the study be kept confidential?

Yes. All information that is collected during the research will be kept strictly confidential and will not be available to anybody outside of the research team. The information will be kept securely according to the standard procedures of the Belfast Trust and Queen's University of Belfast.

What will happen to the results of the research study?

We plan to use the results to find out the importance of a patient's pelvic position during hip operations. We would hope to publish any results in scientific journals and present them at local and international meetings. The identity of any participant will not be disclosed when the results are published. In particular results from this study will form an important part of a PhD thesis.

What will happen if I do not want to carry on with the study?

You can withdraw from the study at any time. Information and results collected until the time you withdraw may still be used.

Who is funding the research?

This study is being funded by the Belfast Arthroplasty Research Trust (BART) and will use existing staff and resources at the Outcomes Unit here at Musgrave Park Hospital.

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The study investigators are:

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Who has reviewed the study?

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PARTICIPANT CONSENT FORM (Patient)

Title of Project: **Evaluation of pelvic position in total hip replacement**

Name of Researcher: **Prof David Beverland (Chief Investigator & Principal Investigator)**

I confirm that I have read and understood the Participant Information Sheet dated 19/05/14 for the above study. I have had time to consider the information, ask questions which have been answered satisfactorily.

Please initial box

I understand that I am free to ask additional questions and if I want any additional information regarding this research and my rights as a research subject, I may speak to the research team or contact the R&D Office at the Belfast Trust.

Please initial box

I understand that lines will be drawn on my lower back and this part of my body will be visible and photographed during the study. I know that photographs will never be taken of my face.

Please initial box

I understand that there is the risk that my stability will be reduced when getting onto the table and standing on blocks but that I will have two members of the research team to aid me in my stability whilst getting on or off the operating table and when stepping on and off the blocks if I wish.

Please initial box

I understand that my medical records may be accessed by investigators to determine whether I am suitable for the study.

Please initial box

I understand that whilst my identity in this study will remain confidential, results from my participation may be used and published.

Please initial box

I understand that participation in this study is voluntary and I may refuse to participate or may discontinue participation at any time without penalty or prejudice to the quality of care which I will receive.

Please initial box

I know that I am free to withdraw at any time without giving any reason, without my medical care or legal rights being affected.

Please initial box

PATIENT NAME (PRINT)

SIGNATURE

DATE

INVESTIGATOR NAME (PRINT)

SIGNATURE

DATE



PARTICIPANT CONSENT FORM (Control)

Title of Project: **Evaluation of pelvic position in total hip replacement**

Name of Researcher: **Prof David Beverland (Chief Investigator & Principal Investigator)**

I confirm that I have read and understand the Participant Information Sheet dated 19/05/14 for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily.

Please initial box

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Please initial box

I know that I am free to withdraw at any time without giving any reason, without my legal rights being affected.

Please initial box

 PATIENT NAME (PRINT)

 SIGNATURE

 DATE

Transverse Pelvic Line Study

Investigators Present

Participant Study Number

Participant Name

Date of Birth

Gender

M**F**

Has participant consented?

Y**N**

Previous Surgery on Hip and or Knee?

Y**N**

Weight (kg)

Adominal Circumference (mm)

Height (m)

Choice of Block (mm)

Comments

Photograph			
1		7	
2		8	
3		9	
4		10	
5		11	
6		12	

Lead Investigator signature: _____

Date: _____